Guide to Hydrological Practices

Volume I

Hydrology – From Measurement to Hydrological Information

World Meteorological Organization
Weather • Climate • Water

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PREFACE

In September 2000, world leaders agreed to the United Nations Millennium Declaration, from which was soon derived a set of eight time-bound and measurable goals and targets for combating poverty, hunger, disease, illiteracy, environmental degradation and gender inequality. These eight objectives are known as the United Nations Millennium Development Goals (MDGs). The attainment of each of these Goals depends, to a great extent, on the availability of appropriate freshwater and on the protection of the population from the ravages of flooding. This, in turn, places a major responsibility on the National Hydrological and Hydrometeorological Services to support the necessary actions at the national level, in the face of ever-increasing demands on the limited freshwater resources available to WMO Members. In transboundary basins, in particular, where concerns are often driven by the need for equitable distribution of these limited resources, appropriate operational mechanisms to share them may have to be established and maintained among the relevant riparian countries.

One of the purposes of the World Meteorological Organization (WMO) is to promote the standardization of meteorological and hydrological observations and to ensure uniform publication of observations and statistics. With this objective, the World Meteorological Congress has traditionally adopted Technical Regulations laying down the meteorological and hydrological practices and procedures to be followed by Members of the Organization. These *Technical Regulations* (WMO-No. 49) are supplemented by a number of manuals and guides describing in more detail the practices and procedures that Members are requested or invited to follow, respectively, in monitoring and assessing their respective water resources. It is therefore hoped that improved uniformity and standardization in hydrological practices and procedures will also contribute to enhanced collaboration among WMO Members and further facilitate regional and international cooperation.

The aim of the *Guide to Hydrological Practices* is to provide the relevant information on current practices, procedures and instrumentation to all those engaged in the field of hydrology, thereby enabling them to carry out their work more successfully. Complete descriptions of the theoretical bases and the range of applications of hydrological methods and techniques are beyond the scope of this guide, although references to such documentation are provided wherever applicable. Detailed procedures for monitoring hydrological parameters are dealt with in the specific WMO Manuals.

It is hoped that this guide will be of use, not only to Members' National Services, but also to various other stakeholders and agencies involved in water resources management in general, and in water resources monitoring and assessment in particular. The WMO Commission for Hydrology (CHy) has therefore decided to make this guide a "living" document, which will be updated periodically and posted on the Internet. This Guide will also represent one of the building blocks of the WMO Quality Management Framework – Hydrology, which is currently being developed in order to support Members and their National Services by ensuring that the activities they undertake, such as hydrological data acquisition or delivery of services and products, are indeed performed efficiently and effectively. Users of the Guide are therefore invited to continue providing their comments and suggestions for its further improvement.

The *Guide to Hydrological Practices* is published in English, French, Russian and Spanish. However, as with previous versions, several Members have announced their intention to translate this Guide into their national languages.

It is a pleasure to express my gratitude to the WMO Commission for Hydrology for taking the initiative to oversee the revision of the *Guide to Hydrological Practices*.

(M. Jarraud)
Secretary-General

ACKNOWLEDGEMENTS

Following the expressed needs of its members, the Commission for Hydrology decided to update and publish this, the sixth edition of the *Guide to Hydrological Practices* (Guide). This decision was made based on comments and experiences in using the fifth edition of the Guide and recognizing its great value to the National Hydrological Services and professionals working in water-related fields. More than 40 seasoned experts from around the world have contributed to the preparation of this edition. As a result, it is oriented towards practical applications and to fit within a quality management framework that is being initiated by the Commission for Hydrology. It is with great pleasure that I express the gratitude of the Commission to those experts who volunteered to be involved in the material compilation and preparation process, and enabled this enormous task to be accomplished.

I extend my deep appreciation to the members of the Review Committee established by the Commission for Hydrology that has overseen the revision of the Guide. The Review Committee headed by Karl Hofius (Germany), and consisting of Suresh Chandra (India), Denis Hughes (South Africa), Fred Kyosingira (Uganda), Paul Pilon (Canada), Marco Polo Rivero (Venezuela) and Avinash Tyagi (Director, Climate and Water Resources Department, World Meteorological Organization (WMO), was instrumental in identifying the areas in the fifth edition that required revision and updating, identifying the experts responsible for redrafting and peer review of various chapters and sections, and carrying out the review of the experts' contributions.

I express my sincere thanks and recognition to the experts who contributed to the redrafting and revision of the Guide. The following experts contributed to the updating and revision of the chapters (indicated in brackets) of Volume I of the Guide: Svein Harsten (Chapters 2 and 5); Robert Halliday (Chapter 2); Chris Collier (Chapter 3); Karan S. Bhatia (Chapter 4); Ahmed Fahmi (Chapter 5); Anthony Navoy (Chapter 6); Anne Coudrain (Chapter 7); Albert Rugumayo (Chapter 8); John Fenwich (Chapter 9); and Matthew Fry and Frank Farquharson (Chapter 10).

Peer review of the material prepared for the chapters was provided by the following experts: Robert Halliday (Chapter 2); Nicholas Kouwen (Chapter 3); Mauro Greppi (Chapter 4); Svein Harsten (Chapter 5); Giovanni Maria Zuppi (Chapter 6); Valerio Vendegna (Chapter 7); Filippo Thierry and Fabio Santamaria (Chapter 8); Maria-Monica Ghioca (Chapter 9); and Bruce Stewart (Chapter 10).

The following experts contributed to the revision of the chapters and sections (indicated in brackets) of Volume II of the Guide: Arni Snorrasson (Chapter 2); Paul Mosley (material taken from Chapter 2); Bruce Mitchell (Chapter 3); Tinus Basson (4.2); Suresh Chandra (4.3); P.B.S. Sarma (4.4); Valdemar Andrade (4.5); Denis Mosnier (4.5); Benno Droge (4.6); Carlos Tucci (4.7); Shankar B. Kulkarni (4.8); Carlos Meier (4.9); Kaz Adamowski (Chapter 5); Zbigniew W. Kundzewicz (Chapter 6); and Curt Barrett, Kosta Georgakakos, Ian Cluckie, Paul Pilon, Sergei Borsch and James Dent (Chapter 7). Contributions on the latest technological developments in remote-sensing were provided by Edwin Engman and Ahalam Shalaby in various chapters.

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The sixth edition of the Guide will be a living document and its Web version will be updated as and when there are significant developments in the practices in any particular field. As it is applied and used in practice, the Guide may be improved through comments and suggestions from the hydrological community. The Commission for Hydrology will endeavour to keep the Guide as up to date as possible by considering the feedback from its members.

(Bruce Stewart)
President, Commission for Hydrology

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Hydrology is the science that deals with the occurrence and distribution of the waters of the Earth in time and space, both above and below the land surface, including their chemical, biological and physical properties, and their interaction with the physical environment (WMO/UNESCO, 1992). It provides an understanding of various phases of water as it passes from the atmosphere to the Earth and returns to the atmosphere. As such, it forms the basis for water resources assessment and management and the solution of practical problems relating to floods and droughts, erosion and sediment transport and water pollution. Increasing stress on the available water resources in the search for improved economic well-being and concerns for the pollution of surface water and groundwater have highlighted the central role of hydrology in all water and environment initiatives.

To provide guidance in monitoring this vital resource, which is central to the development and well-being of humankind, the World Meteorological Organization (WMO) Commission for Hydrology, at its first session (Washington DC, 1961), recognized the urgent need for the preparation of a guide to the relevant operational practices. As a result, the first edition was published in 1965 as the *Guide to Hydrometeorological Practices*.

The second and third editions of the Guide were published in 1970 and 1974, respectively. The third edition was entitled *Guide to Hydrological Practices* in recognition of the broader scope of its contents. Subsequently, during its fifth session (Ottawa, 1976), the Commission approved the revision of and substantial additions to the Guide to produce a fourth edition, which was issued in two volumes. Volume I dealt with data acquisition and processing and Volume II with analysis, forecasting and other applications. Volumes I and II of the fourth edition were published in 1981 and 1983, respectively. With the evolution of technology, and the evolution of the Hydrology and Water Resources activities within WMO, the fifth edition of the Guide was published in 1994 as one consolidated volume. It was also published on a CD-ROM for easy outreach to a wider water management community, beyond the traditional WMO constituency.

In 1999, the World Meteorological Congress adopted “Weather, Climate and Water” as the official subtitle of the Organization and the Commission for Hydrology, at its eleventh session in Abuja, Nigeria, in 2000, recommended that the sixth edition of the Guide be published as a live document to be uploaded to the Internet and updated more frequently, as and when required.

1.2 SCOPE

The accepted principles of integrated water resources management dictate that, in order to achieve environmental sustainability and economic productivity, rivers must be managed at the basin level. Today, when water is perceived to be everybody’s business, various stakeholders, at the national as well as at international level, participate and play important roles in the process. Many institutions and agencies within a country are engaged in the collection of hydrological data and information. These data may be collected by various agencies using different measurement procedures. The resulting lack of homogeneity in the observations gives rise to a lack of confidence. It is imperative, therefore, that all these partners be made aware of the manner in which the hydrological data are collected, the limitations and the reliability of the data, and how they are to be managed by the responsible organizations in the basin. Transparency in data collection, storage and sharing is an essential element for cooperation among various users. A quality management framework for hydrometry and hydrological information is fundamental in using hydrological information from diverse sources.

The growing demand for freshwater resources has increasingly focused the attention of governments and civil society on the importance of cooperative management. Sharing the benefits of cooperation and even conflict prevention stem from a broad understanding of the principles and mechanisms through which these results can be achieved. Transboundary rivers have the potential to bring countries together both economically and politically or, conversely, they can cause economic and political tensions. The risk factor in decision-making in water resources management is a function of hydrological variability. The risks can be mitigated through cooperative management of transboundary rivers. Cooperation in transboundary river management is fundamentally a political activity. Allocation of the resources or distribution of the benefits is essentially dependent on the knowledge of water availability and the related hydrological variability. A shared and accepted knowledge of the resources, their projected availability and the confidence in their accuracy greatly help in assessing the feasibility and fairness of alternative management and investment scenarios.

A lack of homogeneity in the data on the land phase of the hydrological cycle limits the scientific capacity to monitor changes relevant to climate and to determine the causes of variability and change in the hydrological regime. River discharge has a role in driving the climate system, as the freshwater flows into the oceans may influence thermohaline circulation. For easy and reliable use, the quality of such data, and the procedures for its acquisition, storage and exchange should in general follow certain specified standards and protocols.

All of these factors increased the need for ensuring the quality of hydrological data. WMO, with a vision to provide expertise in international cooperation in weather, climate, hydrology and water resources, issues international guidance material and standards, and it is hoped that this Guide will form an important link in the quality management framework for hydrological practices. To meet such requirements, continuing efforts have been made to expand and improve the Guide, now in its sixth edition. It is expected that this Guide will be useful to agencies – not only to National Hydrological Services, but also to other stakeholders.

This Guide addresses all aspects of the land phase of the hydrological cycle, especially its phases upon and under the surface of the land. In conjunction with the manuals published by WMO, it provides detailed information on those areas that fall within the scope of the hydrology and water resources activities of the Organization designed to support National Hydrological Services and services with a similar mission.

The Guide forms part of an overall framework of recommended practices and procedures provided by *Technical Regulations* (WMO-No. 49) Volume III – Hydrology, as approved by WMO. Members are invited to implement these recommended practices and procedures in developing their Hydrological Services and activities.

1.3 CONTENTS OF THE GUIDE

It is difficult to set a clear dividing line between the science of hydrology and the practice of water resources planning and management. Nevertheless, for very practical reasons, it was necessary to divide this edition of the Guide into two volumes as explained below (Figure I.1).

Volume I, entitled Hydrology – From Measurement to Hydrological Information, deals with networks, instruments, methods of observation and primary data processing and storage. It contains ten chapters, beginning with an introduction and an outline of the contents in Chapter 1.

Chapter 2, entitled Methods of observation, deals with the design and evaluation of hydrological networks and provides an overview of instruments and methods of observation for various hydrological elements that are described in detail in the subsequent chapters. Precipitation measurement in Chapter 3 is covered in all its aspects ranging from the location of raingauges to the observation of precipitation by remote-sensing. The chapter covers both liquid and solid precipitation, including their quality. Chapter 4, Evaporation, evapotranspiration and soil moisture, addresses both direct and indirect methods and also briefly reviews methods for evaporation reduction.

Chapter 5, Surface Water Quantity and Sediment measurement, is pivotal and deals with measurement of flow in rivers and the capacity of lakes and reservoirs. It is also concerned with the measurement of sediment discharge. This subject matter is discussed in greater detail in the *Manual on Stream Gauging* (WMO-No. 519) and the *Manual on Operational Methods for the Measurement of Sediment Transport* (WMO-No. 686), to which the reader is invited to refer for more information.

Chapter 6, which is entitled Groundwater, is concerned with measurements from wells and the hydraulic properties of aquifers. It also looks in some detail at various remote-sensing techniques for groundwater observation.

The development of water resources is not only constrained by their availability in quantity but also by their quality. Accordingly, Chapter 7, Water quality and aquatic ecosystems, addresses subjects ranging from sampling methods to remote-sensing. Chapter 8, Safety considerations in hydrometry, discusses all the topics ranging from the safety of the personnel performing the measurements to

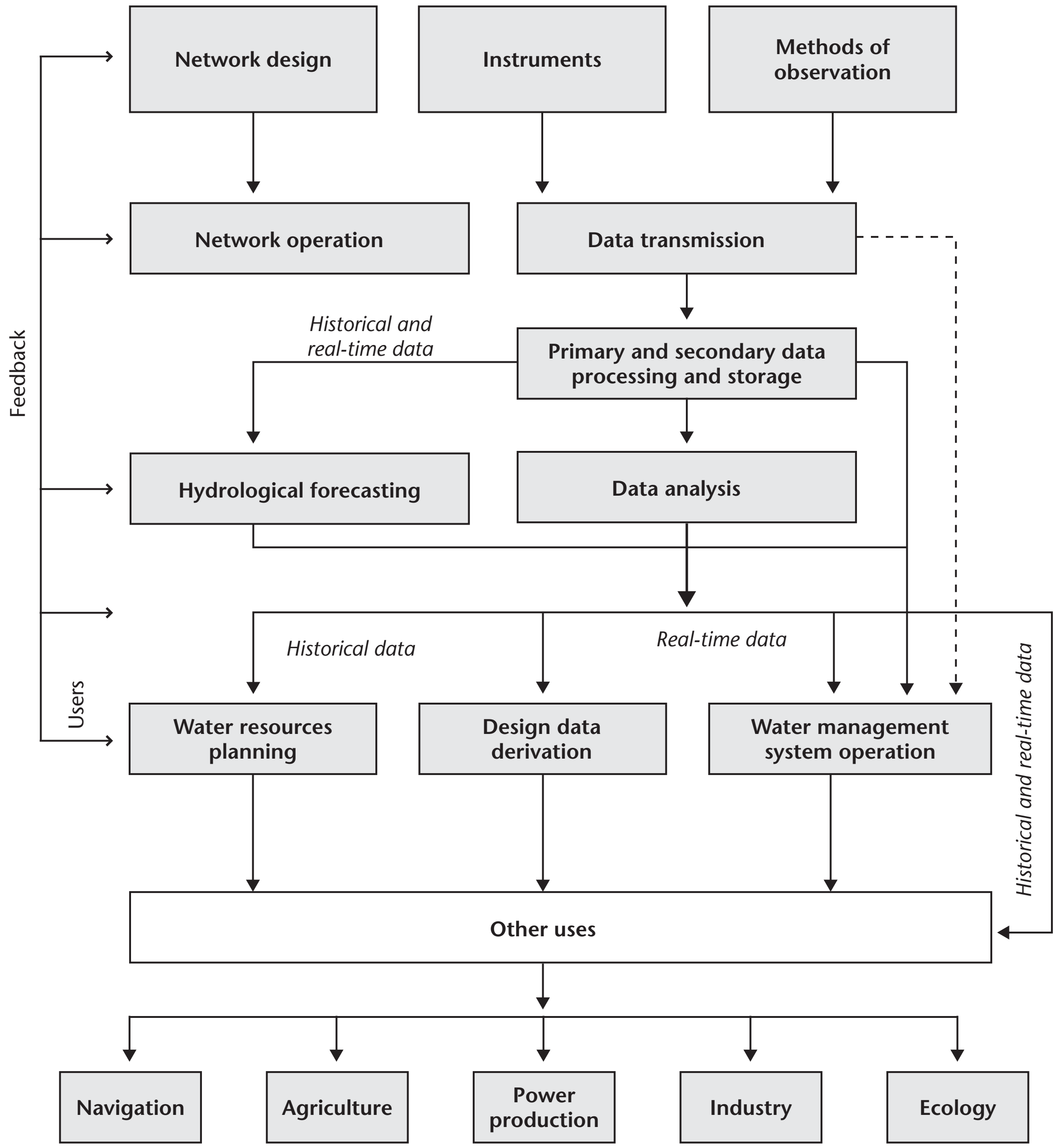

Figure I.1.1. System of hydrology

safeguarding recording stations and the samples collected.

Lastly, Chapters 9 and 10, Data processing and quality control and Data storage, access and dissemination, respectively, include the dissemination of data for use by the wider water community.

Volume II deals with the application of the information referred to above in hydrological forecasting and the planning and design of various water projects. Accordingly, the volume is entitled Management of Water Resources and Application of Hydrological Practices. It consists of seven chapters beginning with an introduction and outline of the contents in Chapter 1.

Chapter 2 provides guidance on the management of hydrological services, including human resources aspects and financial and asset management. Chapter 3 introduces integrated water resources management and emphasizes the vital role of quality hydrological data in addressing various complex water management issues. Chapter 4 highlights the use of hydrological information in applications to water management, namely estimating reservoir capacity and yield, flood management, irrigation and drainage, hydropower and energy-related projects, navigation and river training, urban water resources management, sediment transport and river channel morphology and environmental issues. Chapter 5 deals with extreme value analysis, and Chapters 6 and 7 address the modelling of hydrological systems and hydrological forecasting, respectively, as two of the key functions of Hydrological Services in water management.

While a measure of standardization is desirable and can be achieved with respect to instruments, methods of observation and publication practices, this is rarely the case with respect to hydrological analysis and applications. Therefore, the emphasis in Volume II is on presenting alternative approaches to the solution of selected problems, which have been demonstrated, through experience, to be both practical and effective. Rather than recommending any approach or technique in preference to another, attention is drawn to the principal features and advantages of each approach. The final choice of approach will depend on a multitude of factors, including the relevant hydrological and climatic regimes, available data and information and the purposes to be served, and can only be made in the light of a full understanding of the individual situation. During the past few years, the increasing availability of microcomputers has permitted the introduction of more sophisticated analytical methods and techniques. Some of these have now been widely adopted in practice and they have therefore been introduced into this Guide.

The space limitations of this Guide restrict the amount of material that can be presented. For more detailed information on the subjects treated, the reader should consult the following publications: for discharge measurement, the *Manual on Stream Gauging* (WMO-No. 519, Volumes I and II) and, on sampling, the *GEMS/Water Operational Guide* (UNEP, 2005). The reader is also referred to international standards dealing with methods for liquid flow measurements in open channels prepared by member countries of the International Organization for Standardization (ISO). ISO has developed more than 50 standards for various types and methods of measurement. Valuable references can also be found in the proceedings of the international symposiums, seminars and workshops on hydrometry organized by the International Association of Hydrological Sciences (IAHS), WMO and the United Nations Educational, Scientific and Cultural Organization (UNESCO).

A full description of the theoretical base for the recommended practices, and detailed discussion of their methods of application are beyond the scope of this Guide. For such details, the reader is referred to appropriate WMO manuals and technical reports, as well as to other textbooks, handbooks and technical manuals of national agencies. In particular, further detailed guidance on instruments and methods of observation is given in the *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8) and the *Guide to Climatological Practices* (WMO-No. 100).

References appear at the end of each chapter.

1.4 THE HYDROLOGICAL OPERATIONAL MULTIPURPOSE SYSTEM

In recent decades, hydrological science and technology have made substantial progress and significant contributions have been made by field hydrologists to the development and management of water resources. So as to facilitate the sharing of hydrological practices among the National Hydrological Services, a technology transfer system known as the Hydrological Operational Multipurpose System (HOMS) was developed by WMO and has been in operation since 1981. It offers a simple but effective means of disseminating information on a wide range of proven techniques for the use of hydrologists. HOMS transfers hydrological technology in the form of separate components. These components can take any form, such as a set of drawings for the construction of hydrological equipment, reports describing a wide variety of hydrological procedures and computer programs covering the processing and storage of hydrological data, as well as modelling and analysis of the processed data. To date, over 180 components have been made available, each operationally used by their originators, thus ensuring that every component serves its purpose and has been proved in practice. These descriptions appear in the *HOMS Reference Manual* (HRM) which is available online at http://www.wmo.int/pages/prog/hwrp/homs/homs_en.html in the English, French, Russian and Spanish languages. The present Guide is further enriched through cross-references to the relevant HOMS components, which are included at the beginning of the relevant sections of this Guide.

References and further reading

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CHAPTER 2

METHODS OF OBSERVATION

2.1 INTRODUCTION – THE HYDROLOGICAL CYCLE AS THE SUBJECT OF OBSERVATION

Water is found on Earth in significant amounts in all three of its physical phases: liquid, solid and gaseous. It is also found in all three of Earth's major environments that are readily accessible to humans: the atmosphere, the seas and oceans, and the land masses. As water can readily move from one environment to another and can change from one phase to another in response to its environment, it is a dynamic medium in both space and time. The Earth's system of repositories for the storage of water and the multitude of paths among the many repositories has been conceptualized as a cycle, as shown in Figure I.2.1. The science of hydrology has not traditionally encompassed the entire hydrological cycle, but has been limited to the land portion of the cycle and its interactions with the oceans and atmosphere.

Because humankind spends a predominant amount of time on the land surface and water is both a necessity for life and a potential hazard to it, hydrological knowledge is valuable in providing for our continuity and well-being. One traditional means by which hydrological knowledge has been accumulated is through measurement of the storage and flow of water at distinct points in time and space. Such measurements, also known as data, are analysed and synthesized to generate hydrological knowledge or information. Volume II of this Guide deals with hydrological analysis.

Two of the basic equations that describe the physics of the hydrological cycle are also pertinent in describing the systems that are used to make measurements of its transient properties: (a) the equation of continuity of mass; and (b) the equation of continuity of energy. For example, one form of the equation of continuity of mass:

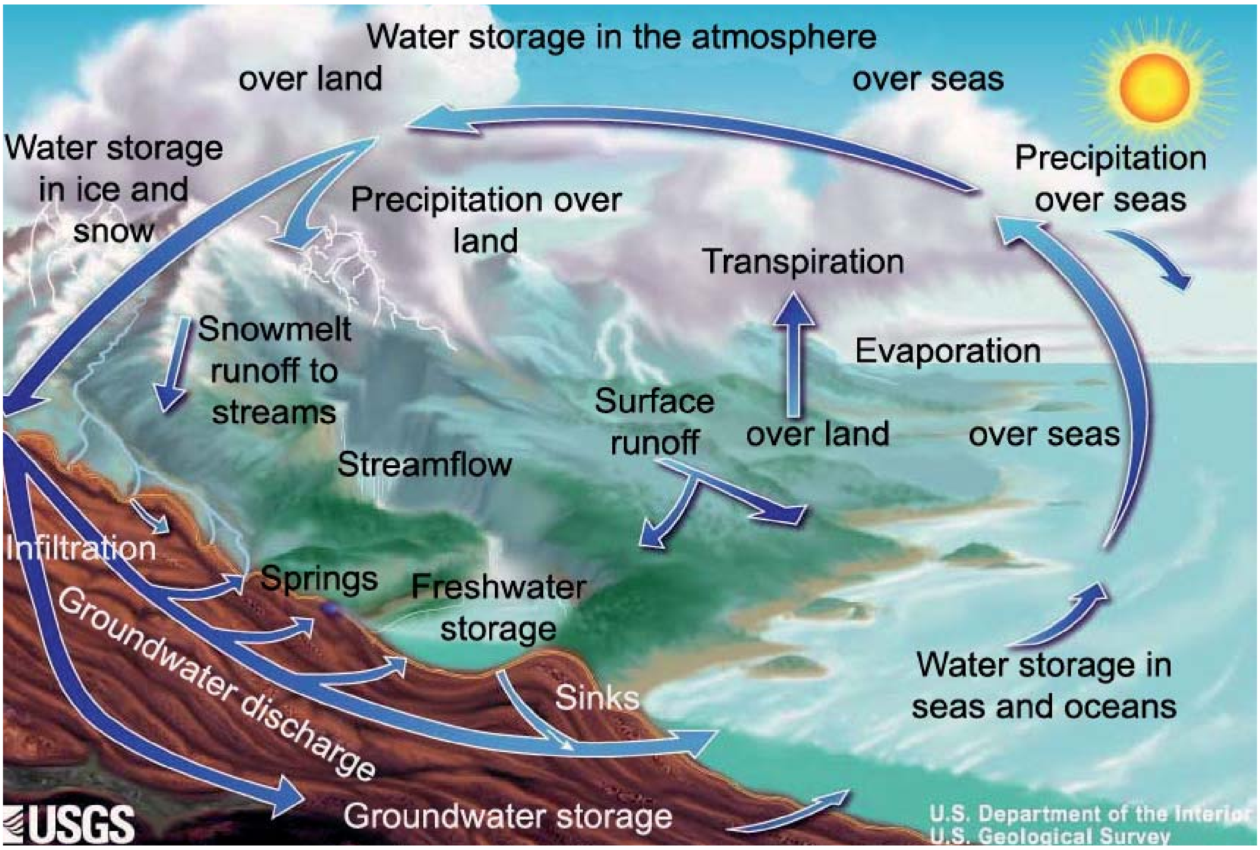


Figure I.2.1. The hydrological cycle

$$Q = AV \tag{2.1}$$

often serves as the basis for the determination of the flow rate in a stream or canal. In this equation, Q is the instantaneous rate of flow through a cross-section of channel with area, A and average flow velocity, V. Traditionally, flow rate, also known as discharge, could not be measured directly for streams of even a modest size. A cross-sectional area, however, can be measured by sampling its spatial dimensions, and velocities can be sensed by the use of current meters. Thus, the use of this equation, described in detail in Chapter 5, has permitted determinations of the rate of discharge of even the largest rivers of the world.

Another example of the role of the equation of continuity of mass can be found in the observation of evaporation of water from a lake surface. In this example, the equation takes the form:

$$P + I - O - E = \Delta S \tag{2.2}$$

where P is the amount of precipitation that falls onto the surface of the lake during a period of observation, I is the inflow of surface water and groundwater during the period, O is the outflow of surface water and groundwater, E is the quantity of water evaporated from the surface of the lake during the period, and ΔS is the change in the volume of water in the lake during the period.

Precipitation can be measured according to the techniques described in Chapter 3; inflows and outflows can be measured using techniques described in Chapters 4, 5 and 6; changes in the lake contents can be computed by relating the lake-surface elevations at the beginning and the end of the observation period to the respective contents at those times; and water-level measurement is discussed in Chapter 5. By measuring or otherwise observing four of the five terms in equation 2.2, the fifth, evaporation, can be computed algebraically.

Systematic hydrological observations are at the very core of the development of databases, information and knowledge required for the effective management of water resources. This chapter discusses a number of subjects that are fundamental to the operation of hydrological and meteorological observing networks and to the production hydrological information.

The chapter provides an overview of hydrological standards and codes, accuracy of measurements, concepts of network planning, methods of observation, measurement of physiographic characteristics, the role of hydrological data in information systems and the linkages to sustainable development. Some of these subjects are discussed in greater detail later in this Volume. Where this is the case, cross-references are provided.

2.2 WATER RESOURCES INFORMATION SYSTEMS

2.2.1 Need for data and information

The report of the International Conference on Water and the Environment (ICWE), held in Dublin in January 1992 (United Nations, 1992*a*), provides a compelling assessment of the importance of water resources to the world's environment and to its economy. Its specific policy statements highlight very effectively the role that hydrological services should play in achieving goals related to sustainable development. ICWE addressed the following issues:

(a) Integrated water resources development and management;
(b) Water resources assessment and impacts of climate change on water resources;
(c) Protection of water resources, water quality and aquatic ecosystems;
(d) Water and sustainable urban development and drinking water supply and sanitation in the urban context;
(e) Water for sustainable food production and rural development, and drinking water supply and sanitation in the rural context;
(f) Mechanisms for implementation and coordination at the global, national, regional and local levels.

Volume II, Chapter 3, reviews the evolution of integrated water resources management and provides examples of best practices. The nature of the information that will be required to meet the needs of integrated water resources management is difficult to project. Perhaps, the best ideas can be gathered from considering recent trends in water management (2.2.4). Since data are gathered for the use of water managers, whether in government or private agencies, changes in the way water is managed will influence the data and information demands.

The impacts of these changes may include:

(a) Growing competition for water, resulting in a higher value being placed on available supplies and, ultimately, goods and services being redefined in terms of their water content – this could be exacerbated by declining water availability and quality in many areas;

(b) Economic pressures resulting in more user fees, cost sharing and local financing of water programmes, with a concurrent shift in emphasis from water development activities to environmental programmes and demand management;
(c) Increased focus on water conservation and reuse in all phases of project development – in some areas, reclaimed water now costs less than freshwater supply;
(d) Environmental legislation designed to hold polluters and users accountable for their impacts on available supplies;
(e) Legal measures to ensure that users and water managers justify their needs, uses and management practices, and that increased priority be accorded to environmental water uses (for example, fish and wildlife habitat) versus the traditional economic uses (for example, agriculture and industry);
(f) Emphasis on basin and regional water planning as a means of resolving transboundary issues and disputes.

These trends indicate that greater coordination of data-collection efforts will be required to meet the needs of water managers in the future. Water management is becoming more integrated across disciplines and specialities; therefore, compatible data on quantity and quality of surface water and groundwater, and on specific basins and regions will be required. Current problems related to data accessibility, compatibility and reliability will have to be resolved to meet these needs. In addition, water management challenges are closely linked to those of environmental management or ecosystem management. Therefore, an increasingly holistic management approach is required.

While many users will continue to need data for design and analysis purposes, increased attention must be paid to the need for comprehensive regional surface-water information that can be applied to many different kinds of water issues and problems. This means that overview information, fact sheets and summaries, surface-water and precipitation mapping, hydrological assessments of basins and regions, and water information relevant to the assessment of water quality and groundwater problems must be available. The use of real-time water data will continue to grow to serve many needs.

2.2.2 Hydrological information systems

This Volume of the Guide deals with the field activities of operational hydrology. However, the data that are generated by the field activities are of little or no value if they cannot be readily and confidently accessed by the potential data users. Operational hydrology within a given Hydrological Service can be considered as an information system providing a conceptual basis for the development of proper approaches, which ensure that the right data are available in the right form at the right place and time. Figure I.2.2 depicts the elements of a hydrological information system. Ideally, the information system is embedded in a natural sequence of actions and decisions that begins with the perception of an opportunity and culminates in the implementation of decisions that maximize the net positive impacts of the opportunity.

A hydrological information system combined with a suite of numerical models – physical, statistical or socio-economic – comprises a decision support system. With the decision support requirements firmly in mind, the designer of the information system can specify the procedures to be used to analyse the hydrological data. These data-analysis technologies may be any one model or a combination of models that account for the probabilistic, stochastic or deterministic natures of the hydrological phenomena of interest. Volume II of this Guide (in particular Chapters 5 to 7) discusses many of these data-analysis technologies.

The actual data collection can begin at this point in the sequence, and it is also at this point that feedback, represented as dashed arrows in Figure I.2.2, begins to take place. All of the previous steps have been based on a specific level of knowledge about the hydrological conditions of interest. As data are collected, this level increases, and new data-analysis techniques and new network designs may become appropriate. Guidance on data collection is given in 2.5.

From Figure I.2.2, it is possible to see that quality assurance is an integral phase of the information system that is relevant throughout the continuum from field activities to the dissemination of data and information. Owing to its pervasive nature, quality-assurance guidance can be found throughout this Volume.

No discussion of information systems is complete without mention of data management systems. The information contained in a robust data-management system is available, not only for the uses for which

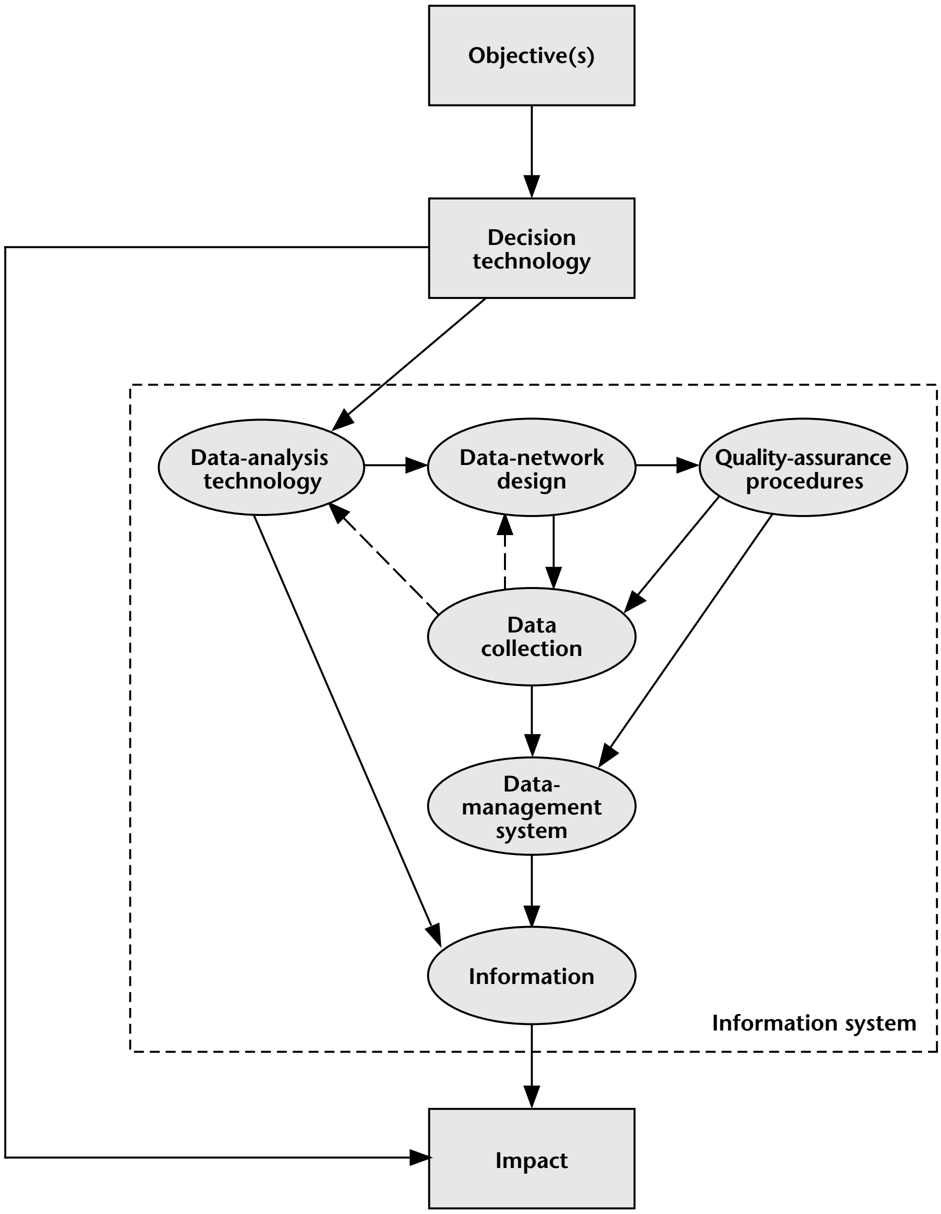


Figure I.2.2. Components of a hydrological information system

the data were collected originally, but also for a multitude of uses that may never have been anticipated. However, with robustness comes a price. The options inherent in robust systems tend to make them difficult to use, as more training is required. This represents the first portion of the price. This part of the cost can be minimized by user-friendly systems designs. The second cost factor is the potential loss of information that robustness entails. As a data-management system cannot be all things to all people, compromises must be made, which usually result in data compaction and loss of data attributes. To reduce such loss, subsystems that retain more objective-specific data can be appended to the robust, central system. Such systems are discussed in Chapter 10. Current technology also allows the development of distributed hydrological information systems having searchable metadata. Provided that computer security matters are fully considered, such virtual data systems provide an effective and robust means of accessing data and information required for decision-making.

The ultimate product of the information system is obtained by processing the data through the same data-analysis technology that was initially crucial in the design of the data network. The sequence culminates by integrating the hydrological information into the decision process for which it was designed to have an optimal impact. The key to obtaining this optimality is the compatibility among the decision technology, the data-analysis technology and the data network.

A well-designed information network contains synergism that is derived in three ways. First, information is a commodity that is not destroyed by its use. Thus, if properly preserved, it can be made available at minimal cost for many uses not anticipated at the time of its collection. Secondly, information can be used to improve understanding of hydrological processes. By improving process understanding, both the information content of the existing data and all future data are increased. Thirdly, synergism evolves by taking advantage of the accomplishments of others. New approaches and technologies for the design of information systems, like the data they contain, are recyclable commodities.

2.2.3 Uses of water resources information

Hydrological or Hydrometeorological Services or related agencies have been established in countries for systematic water resources data collection, archiving and dissemination described elsewhere in this Volume. Their primary role is to provide information to decision makers on the status of and trends in water resources. Such information may be required for the following purposes (WMO/UNESCO, 1991):

(a) Assessing a country's water resources (quantity, quality, distribution in time and space), the potential for water-related development and the ability of the supply to meet actual or foreseeable demand;
(b) Planning, designing and operating water projects;
(c) Assessing the environmental, economic and social impacts of existing and proposed water resources management practices and planning sound management strategies;
(d) Providing security for people and property against water-related hazards, particularly floods and droughts;
(e) Allocating water among competing uses, both within the country and cross-border;
(f) Meeting regulatory requirements.

Most frequently, water resources information has been collected for a specific purpose, such as the design of a hydroelectricity scheme. However, increasing competition among users for scarce water requires that resources be managed in an integrated fashion, so that the interactions among several projects and users may be understood. This places a much greater burden on the suppliers of water resources information, because a variety of types of information is simultaneously needed, and has to be presented in different forms for different users. This makes it essential that assessment agencies understand the needs of all their users, and not just those with whom they have traditionally dealt. Even more demanding is the need to look ahead to the possible needs of future users of data and to commence collecting the information before an actual demand can be demonstrated with certainty. Therefore, it is necessary that the design and updating of data-collection networks, especially the principal stations, be coordinated to ensure that stations for monitoring the various elements of the water cycle are sufficiently related, both in number and location, to achieve an integrated network (2.4). Such an approach would enhance the information content of the data sets for both current and unforeseen future needs.

With the growing recognition of such issues as global climate change and the environmental impacts of human activities, such as urbanization, there is an increasing emphasis upon the information required as a foundation for sustainable development and management of water resources. Volume II, Chapter 3, describes the rationale for integrated water resources management and presents elements of best practice.

2.2.4 Types of water resources information

The diversity of possible uses of water resources information implies that there is a considerable range of types of data. Conventional water resources information comprises the statistics of a variety of meteorological and hydrological elements. The elements include the following (WMO/UNESCO, 1991):

(a) Precipitation, for example, rainfall, snow and fog drip;
(b) River levels and flows, and lake and reservoir levels;
(c) Groundwater levels;
(d) Evapotranspiration;
(e) Sediment concentrations and loads in rivers;
(f) Water quality (bacteriological, chemical; and physical) of surface water and groundwater.

The statistics include the following:

(a) Mean annual, monthly, or seasonal values;
(b) Maxima, minima and selected percentiles;
(c) Measures of variability, such as the standard deviation;
(d) Continuous records in the form, for example, of a river flow hydrograph.

There is a requirement for both historical and real-time data to cater to the full range of needs from water resources planning to project design and flood warning. Flood or low flow forecasting (Volume II, Chapter 7) may require data to be synthesized for the future by using numerical flow-routing models (Volume II, 6.3.4).

The *Water-resource Assessment Activities: Handbook for National Evaluation* (UNESCO/WMO, 1988) recognizes a number of types of water resources projects for which hydrological information is required, as given in Table I.2.1.

Together, these imply a vast range of water-related data and information that the Hydrological Services and other related agencies may be required to collect and archive. Different countries have different priorities that depend on their level of economic and social development, the sensitivity of their natural environments to disturbance by human activity, and the nature of the physical environment itself, for example, climate, topography and the abundance or otherwise of water.

There are several critical requirements for an effective water resources assessment programme:

(a) Data of high quality must be collected to permit confident statistical analysis;
(b) The data and the information that they provide must be carefully targeted to the requirements of users;
(c) An integrated observation programme, in which measurements of several variables are made simultaneously, is required to provide the greatest total value;
(d) Other forms of information that are compatible with and can be analysed with water resources information should be available;

Table I.2.1. Hydrological information required for water resources projects

Water projects	*Water levels*			*River flow*			*Sediment*			*Water quality*[a]		
	time series	*max*	*min*	*time series*	*max*	*min*	*time series*	*max*	*min*	*time series*	*max*	*min*
Redistribution of water (diversions, intakes, canals)	M	M	M	H	H	H	H	M	M	H	M	M
Redistribution of water in time (reservoirs)	M	M	M	H	H	H	H	M	M	H	M	M
Energy production (hydropower, waste heat disposal)	H	M	M	H	M	H	H	M	M	M	M	M
Water confiners (dams, flood banks)	H	H	M	M	H	M	M	M	M	M	M	M
Water relievers (spill ways)	M	H	M	H	H		M			M		
Quality improvements (water and sewage treatment)				H	M	H	M	M	M	H	H	H
Zoning (flood plain, scenic rivers)	H	H	M	M	H	M	M					
Insurance (flood damage, water quality damage)	H	H		H	H					H	H	
Flow and level forecasts (flood control, reservoir operation)	H	H	H	H	H	H						
Standards and legislation (water quality)	M	H	H	M	H	H				H	H	H

[a] Water-quality parameters are diverse depending on the type of project.
H = High level of priority M = Medium level of priority

(e) An effective system is needed for archiving and disseminating data to ensure that they are not lost or corrupted and that they are made available in a form that enables analysis (Chapter 10).

The above requirements can be met by the application of contemporary technologies – for example, telemetry, to make data available in near-real time – by implementing searchable computer databases, by remote-sensing to collect areal information more effectively and by Geographical Information Systems (GIS) (2.6.7) to provide a means of analysing spatial data. At the same time, new computer storage devices and the use of the Internet make the data more readily available. Nevertheless, technology is not the only requirement, and a trained and well-managed staff is of even more fundamental importance. As financial resources become increasingly limited in many countries, it becomes ever more vital that effective organizational structures are in place to ensure that those resources are used most efficiently.

In addition to the more conventional measurements, there is a growing recognition of the need to measure other aspects of the freshwater environment and of the wider environment in which freshwater is only a single component. These include:

(a) The volumes of water needed for industrial, domestic and agricultural use, and for navigation. These are now significant modifiers of the hydrological cycle in many basins;
(b) Attributes of rivers and required volumes of water related to instream uses, for example, freshwater fishery habitats or recreation;
(c) Watershed characteristics that may be related to hydrology, for example, vegetation patterns, soil moisture, topography and aquifer characteristics;
(d) Environmental concerns, for example, eutrophication of lakes and damage to natural freshwater and estuarine ecosystems.

2.3 HYDROLOGICAL SYMBOLS, CODES AND ACCURACY OF MEASUREMENTS

2.3.1 Units and symbols

Standardization of units and symbols is desirable and can be achieved through the use of those recommended in Tables I.2.2–I.2.4 (ISO, 1993). Commonly used units and conversion factors are also given. All symbols and units used in the Guide conform to those in the tables.

2.3.2 Hydrological codes

2.3.2.1 General

All systems for the transmission of data make use of some form of coding method, the purpose of which is to ensure that the information is transmitted quickly and reliably (9.3). In the case of fully automated systems, the information must be put into coded form before being processed. For these reasons, the codes are composed of standard forms that enable the information to be transmitted and given in a form compatible with processing. Such processing is usually preceded by quality control (9.8).

The structure of international codes is governed by convention, and codes are developed as a collective effort. For a long time, WMO has been developing codes to meet requirements for the exchange of meteorological data.

In operational hydrology, requirements for data are not on a worldwide scale and yet there have been a multiplicity of codes introduced in this field. This led the WMO Commission for Hydrology to develop international hydrological codes. The purpose of these codes is to cover general requirements so that, as far as possible, the procedures for coding and collecting hydrological data are standardized. The HYDRA and HYFOR codes, which were developed and used in the past, are no longer recommended for use. Instead, the character form for the representation and exchange of data (CREX) code has been developed in recent years for use in the representation and transmission of hydrometeorological data.

This code may be found to be particularly useful in the case of large national and international basins, in which a large number of stations are connected to a processing centre. The observations are coded, usually manually, by an observer, and then transmitted to a collecting centre for processing.

2.3.2.2 Character form for the representation and exchange of data

CREX is the name of a character code for the representation and exchange of meteorological, hydrological and water-quality data. Although originally designed for the exchange of data for which there were no suitable existing WMO code forms, CREX has been used recently as standard code form for data transmitted from data-collection platforms (DCPs). A CREX message shall consist of one or more subsets of related meteorological data defined, described and represented by a single CREX entity. For observational data, each subset shall correspond

Table I.2.2. Recommended symbols, units and conversion factors

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
			Units			
Item	*Element*	*Symbol*	*Recommended*	*Also in use*	*Conversion factor**	*Remarks*
1	Acceleration due to gravity	g	m s^{-2}	ft s^{-2}	0.305	ISO
2	Albedo	r	Expressed as a decimal			
3	Area (cross-sectional) (drainage basin)	A	m^2	ft^2	0.0929	ISO
			km^2	acre ha $mile^2$	0.00405 0.01 2.59	ISO
4	Chemical quality		mg l^{-1}	ppm	~ 1	For dilute solutions
5	Chezy coefficient $[v\ (R_h S)^{-1/2}]$	C	$m^{1/2}$ s^{-1}	$ft^{1/2}$ s^{-1}	0.552	ISO
6	Conveyance	K	m^3 s^{-1}	ft^3 s^{-1}	0.0283	ISO
7	Degree day	D	Degree day	Degree day	Conversion formula: °C = 5/9 (°F–32)	Column IV is based on °C scale and column V on °F scale
8	Density	p	kg m^{-3}	lb ft^{-3}	16.0185	ISO
9	Depth, diameter, thickness	d	m cm	ft in	0.305 2.54	ISO
10	Discharge (river-flow) (wells)	Q Q_{we}	m^3 s^{-1} l s^{-1}	ft^3 s^{-1} gal (US) min^{-1}	0.0283 0.063	ISO
	(unit area–$Q\ A^{-1}$, or partial)	q	m^3 s^{-1} km^{-2} l s^{-1} km^{-2}	ft^3 s^{-1} $mile^{-2}$	0.0109 10.9	ISO
11	Drawdown	s	m cm	ft	0.305 30.5	
12	Dynamic viscosity (absolute)	η	N s m^{-2}			ISO Pa, s, kg m^{-1} s^{-1} also in use
13	Evaporation	E	mm	in	25.4	
14	Evapotranspiration	ET	mm	in	25.4	
15	Froude number	Fr	Dimensionless number			ISO
16	Head, elevation	z	m	ft	0.305	ISO
17	Head, pressure	h_p	m	kg (force) cm^{-2} lb (force) in^{-2}	10.00 0.705	
18	Head, static (water level) = $z + h_p$	h	cm	ft	30.05	ISO
		h	m		0.305	
19	Head, total = $z + h_p + h_v$	H	m	ft	0.305	ISO
20	Head, velocity = $v^2\ (2g)^{-1}$	h_v	cm m	ft	30.05 0.305	

(continued)

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
21	Hydraulic conductivity (permeability)	K	cm s^{-1}	m d^{-1}	0.00116	
				ft min^{-1}	0.508	
22	Hydraulic diffusity = TC_s^{-1}	D	cm^2 s^{-1}			
23	Hydraulic radius = $A\ P_w^{-1}$	R_h	m	ft	0.305	ISO
24	Ice thickness	d_g	cm	in	2.54	
25	Infiltration	f	mm	in	25.4	
26	Infiltration rate	I_f	mm h_{-1}	in h_{-1}	25.4	
27	Intrinsic permeability	k	10^{-8} cm^2	Darcy	0.987	
28	Kinematic viscosity	v	m^2 s^{-1}	ft^2 s^{-1}	0.0929	ISO
29	Length	l	cm	in	2.54	ISO
			m	ft	0.305	
			km	mile	1.609	
30	Manning's coefficient = $R_h^{2/3}\ S^{1/2}\ v^{-1}$	n	s $m^{-1/3}$	s $ft^{-1/3}$	1.486	ISO l/n = k roughness coefficient can also be used
31	Mass	m	kg	lb	0.454	ISO
			g	oz	28.35	
32	Porosity	n	%			α may also be used if needed
33	Precipitation	P	mm	in	25.4	
34	Precipitation intensity	I_p	mm h^{-1}	in h^{-1}	25.4	
35	Pressure	p	Pa	hPa	100.0	See item 17
				mm Hg	133.3	
				in Hg	3386.0	
36	Radiation** (quantity of radiant energy per unit area)	R	J m^{-2}	ly	4.187 x 10^4	
37	Radiation intensity** (flux per unit area)	I_R	J m^{-2} s^{-1}	ly min^{-1}	697.6	
38	Radius of influence	r_2	m	ft	0.305	
39	Recession coefficient	C_r	Expressed as a decimal			

(continued)

I	II	III	IV	V	VI	VII
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
40	Relative humidity (moisture)	U	%			
41	Reynolds number	R_e		Dimensionless number		ISO
42	Runoff	R	mm	in	25.4	
43	Sediment concentration	c_s	kg m^{-3}	ppm	Depends on density	
44	Sediment discharge	Q_s	t d^{-1}	ton (US) d^{-1}	0.907	
45	Shear stress	τ	Pa			ISO
46	Slope (hydraulic, basin)	S		Dimensionless number		ISO
47	Snow cover	A_n	%			
48	Snow depth	d_n	cm	in	2.54	
49	Snow melt	M	mm	in	25.4	Normally expressed as daily
50	Soil moisture	U_s	% volume	% mass	Depends on density	
51	Soil moisture deficiency	$U's$	mm	in	25.4	
52	Specific capacity = $Q_{we}\,s^{-1}$	C_s	m^2 s^{-1}	ft^2 s^{-1}	0.0929	
53	Specific conductance	K	µS cm^{-1}			at θ = 25°C
54	Specific yield	Y_s		Expressed as a decimal		
55	Storage	S	m^3	ft^3	0.0283	
56	Storage coefficient (groundwater)	C_S		Expressed as a decimal		
57	Sunshine	n/N		Expressed as a decimal		Actual (n)/possible (N) hours
58	Surface tension	σ	N m^{-1}			ISO
59	Temperature	θ	°C	°F	Conversion formula °C = 5/9 (°F–32)	ISO t also in use
60	Total dissolved solids	m_d	mg l^{-1}	ppm	~ 1	For dilute solutions
61	Transmissivity	T	m^2 d^{-1}	ft^2 d^{-1}	0.0929	
62	Vapour pressure	e	Pa	hPa mm Hg	100.0 133.3 3386.0	
63	Velocity (water)	v	m s^{-1}	ft s^{-1}	0.305	ISO
64	Volume	V	m^3	ft^3 acre ft	0.0283 1230.0	ISO

(continued)

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
65	Water equivalent of snow	w_n	mm	in	25.4	
66	Weber number	W_e	Dimensionless number			
67	Wetted perimeter	P_w	m	ft	0.305	
68	Width (cross-section, basin)	b	m km	ft mile	0.305 1.609	ISO
69	Wind speed	u	m s^{-1}	km h^{-1} mile h^{-1} k_n (or kt)	0.278 0.447 0.514	
70	Activity (amount of radioactivity)	A	Bq (Becquerel)	Ci (Curie)	3.7 x 10^{10}	IAEA
71	Radiation fluence (or energy fluence)	F	J m^{-2}	erg cm^{-2}	10^3	IAEA
72	Radiation flux intensity (or energy flux intensity)	I	J m^{-2} s^{-1}	erg cm^{-2} s^{-1}	10^3	IAEA

Note: Where international symbols exist, these have been used where appropriate and are indicated as ISO in the last column.
* Column IV = Conversion factor (Column VI) x Column V
** General terms. For detailed terminology and symbols, see the *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8).

Table I.2.3. Miscellaneous symbols

Item	*Unit*	*Symbol*	*Remarks*
1	Concentration	c	ISO
2	Coefficient (in general)	C	ISO
3	Difference	Δ	ISO, values expressed in same units
4	Inflow	I	
5	Lag time	Δt	various units
6	Load	L	
7	Number of (or rank)	m	ISO
8	Outflow	O	
9	Recharge	f	(See item 25 in Table I.2.2)
10	Total number	N	

Table I.2.4. Recommended units as appearing in Table I.2.2.

Item	*Unit*	*Symbol*	*Remarks*
1	Centimetre	*cm*	ISO
2	Day	*d*	ISO
3	Degree Celsius	˚*C*	ISO
4	Gram	*g*	ISO
5	Hectare	*ha*	
6	Hectopascal	*hPa*	ISO
7	Hour	*h*	ISO
8	Joule	*J*	ISO
9	Kilogramme	*kg*	ISO
10	Kilometre	*km*	ISO
11	Knot	*kn, kt*	
12	Litre	*l*	ISO
13	Metre	*m*	ISO
14	Microsiemens	μ*S*	
15	Milligram	*mg*	ISO
16	Millimetre	*mm*	ISO
17	Minute	*min*	ISO
18	Newton	*N*	ISO
19	Parts per million	*ppm*	
20	Pascal	*Pa*	ISO
21	Percentage	*%*	
22	Second	*s*	ISO
23	Tonne (metric ton)	*t*	ISO
24	Year	*a*	ISO
25	Bequerel	*Bq*	IAEA

to one report. CREX uses many of the principles of the previous BUFR code, and each message consists of sections as follows:

Section number	*Name*	*Contents*
0	Indicator section	CREX
1	Data description section	CREX master table number, edition number, table version number, data category, then a collection of descriptors which define the form and content of data subsets making the data section and an optional check digit indicator E
2	Data section	A set of data items defined by section 1
3	Optional section	SUPP followed by additional items for local use
4	End section	7777

Further information can be found at http://www.wmo.int/pages/prog/www/WMOCodes.html.

2.3.3 Accuracy of hydrological measurements

2.3.3.1 Basic principles

Theoretically, the true values of hydrological elements cannot be determined by measurements because errors of measurement cannot be eliminated completely. The uncertainty in measurement has a probabilistic character that can be defined as the interval in which the true value is expected to lie with a certain probability or confidence level. The width of the confidence interval is also called error band.

If measurements are independent one from the other, the uncertainty in the results of measurements can be estimated by taking at least

20–25 observations and calculating the resulting standard deviation, and then determining the confidence level of the results. This procedure cannot usually be followed in hydrometric measurements, because of the change in the value to be measured during the measuring period. For instance, many consecutive measurements of discharge with current meters at constant stage is clearly impracticable in field conditions. Thus an estimate of the uncertainty has to be made by examining the various sources of errors in the measurement.

Another problem in applying statistics to hydrological data arises from the assumption that observations are independent random variables from a fixed statistical distribution. This condition is seldom met in hydrological measurements. River flow is, by nature, not purely random. It depends on previous values. It is generally accepted that some aspects of the departure of hydrological data from the theoretical concept of errors is not serious. However, it should be stressed that no statistical analysis can replace correct observations, in particular because spurious and systematic errors cannot be eliminated by such analysis. Only random errors can be characterized by statistical means.

Section 2.3.3 contains definitions of basic terms related to the accuracy of hydrological measurements. Methods for estimating uncertainty are introduced and numerical values of accuracy, required for the most important hydrological parameters, are given. References to the existing recommendations contained in the *Technical Regulations* (WMO-No. 49) and other publications are also included.

2.3.3.2 Definitions of terms related to accuracy

The definitions of the terms related to accuracy given below take into account those given in the *Technical Regulations* (WMO-No. 49), Volume III – Hydrology and in the *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8):

Accuracy: The extent to which a measurement agrees with the true value. This assumes that all known corrections have been applied.

Confidence interval: The interval which includes the true value with a prescribed probability and is estimated as a function of the statistics of the sample (Figures I.2.3 and I.2.4).

Confidence level: The probability that the confidence interval includes the true value (Figures I.2.3 and I.2.4).

Correction: The value to be added to the result of a measurement to allow for any known systematic error and thus obtain a closer approximation to the true value.

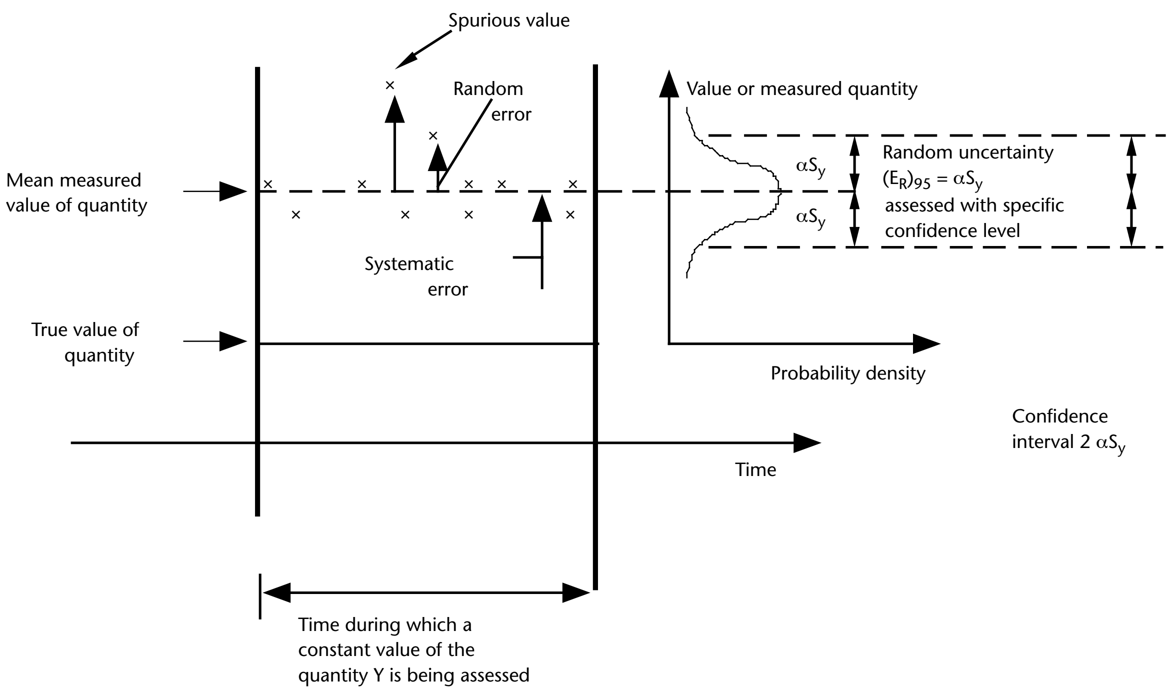


Figure I.2.3. Explanation of errors

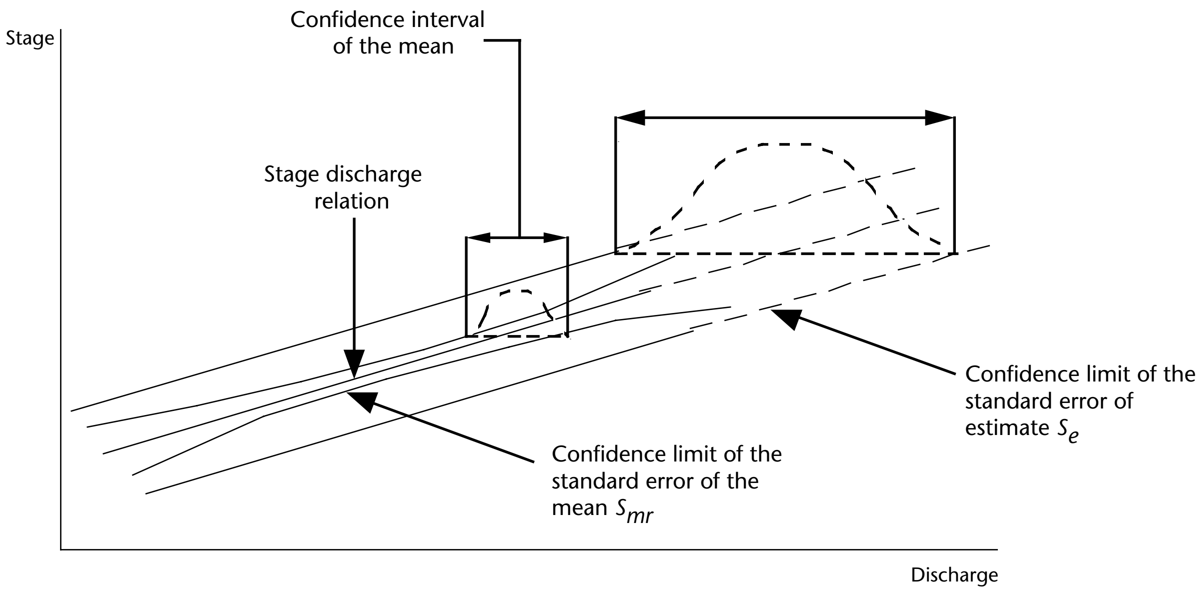


Figure I.2.4. Explanation of errors in linear regression

Error: The difference between the result of a measurement and the true value of the quantity measured. This term is also used for the difference between the result of a measurement and the best approximation of the true value, rather than the true value itself. The best approximation may be a mean of several or many measurements.

Expected value: The best approximation of the true value, which may be a mean of several, or of many measurements.

Hysteresis (instrument): That property of an instrument whereby it gives different measures, for the same actual value, according to whether that value has been reached by a continuously increasing or continuously decreasing change of the variable.

Measurement: An action intended to assign a number as the value of a physical quantity in stated units. The result of a measurement is complete if it includes an estimate (necessarily in statistical terms) of the probable magnitude of the uncertainty.

Normal distribution: A mathematically defined, symmetrical, bell-shaped, continuous distribution, traditionally assumed to represent random errors.

Precision: The closeness of agreement between independent measurements of a single quantity obtained by applying a stated measurement procedure several times under prescribed conditions. Accuracy has to do with closeness to the truth, precision has to do only with closeness together. Precision of observation or of reading is the smallest unit of division on a scale of measurement to which a reading is possible either directly or by estimation.

Random error: That part of the error that varies in an unpredictable manner, in magnitude and in sign, when measurements of the same variable are made under the same conditions (Figure I.2.3).

Range: The interval between the minimum and maximum values of the quantity to be measured, for which the instrument has been constructed, adjusted or set. It can be expressed as a ratio of maximum and minimum measurable values.

Reference measurement: A measurement utilizing the most advanced state of science and the latest technologies. The result of the reference measurement is used to estimate a best approximation to the true value.

Repeatability: The closeness of agreement, when random errors are present, between measurements of the same value of a quantity obtained under the same conditions, that is, the same observer, the same instrument, the same location, and after intervals of time short enough for real differences to be insignificant.

Reproducibility: The closeness of agreement between measurements of the same value of a quantity obtained under different conditions, for example, different observers, instruments, locations, and after intervals of time long enough for erroneous differences to be insignificant.

Resolution: The smallest change in a physical variable that causes a variation in the response of a measuring system.

Sensitivity: The relationship of the change of the response to the corresponding change of the stimulus, or the value of the stimulus required to produce a response exceeding, by a specified amount, the response already present due to other causes.

Spurious value: Value known for certain to be in error, for example, due to human mistakes or instrument malfunction (Figure I.2.3).

Standard deviation (S_y): This is a measure of the dispersion of values about their mean. It is defined as the positive square root of the sum of the squares of the deviation from the arithmetic mean, divided by $(n - 1)$. It is given by:

$$S_y = \left[\frac{\sum_{1}^{n} (y_i - \bar{y})^2}{n - 1} \right]^{1/2} \tag{2.3}$$

where $\bar{y}$ is the arithmetic mean of the sample of n independent measurement of the variable y, and $(n - 1)$ indicates the loss of one degree of freedom.

Standard error of estimate (S_e): A measure of the variation or scatter of the observations about a linear regression. It is numerically similar to the standard deviation except that the linear-regression relation replaces the arithmetic mean and $(n - 1)$ is replaced by $(n - m)$:

$$S_e = \left[\frac{\sum (d)^2}{n - m} \right]^{1/2} \tag{2.4}$$

where d is the deviation of an observation from the computed regression value, m is the number of constants in the regression equation, and $(n - m)$ represent the degrees of freedom in the equation derivation.

Systematic error: That part of the error that either:

(a) Remains constant in the course of a number of measurements of the same value of a given quantity; or
(b) Varies according to a definite law when conditions change (Figure I.2.3).

Tolerance: The permissible accuracy in the measurement of a specified variable.

Tolerance limit: The limiting lower or upper value specified for a quantitative characteristic.

True value: The value that characterizes a quantity in the conditions that exist at the moment when that quantity is observed. It is an ideal value that could be known only if all causes of error were eliminated.

Uncertainty: The interval about the measurement within which the true value of a quantity can be expected to lie with a stated probability (Figure I.2.3). The numerical value of uncertainty is a product of the true standard deviation of the errors and a numerical parameter depending on the confidence level:

$$e = \pm \alpha\sigma_y \approx \alpha s_y \tag{2.5}$$

The standard deviation, s_y, computed from n observations, approaches the true standard deviation, σ_y, as n approaches infinity. In the case of normal distribution of error, numerical parameters are as follows:

Confidence level	α
0.50	0.674
0.60	0.842
0.66	0.954
0.80	1.282
0.90	1.645
0.95	1.960
0.98	2.326
0.99	2.576
0.999	3.291

2.3.3.3 Types of error

Spurious errors should be eliminated by discarding the values of measurements concerned.

These errors can be identified by a statistical-outlier test, such as the one described in ISO 5168 (ISO, 2005) that gives a rejection criterion.

Systematic error originates mainly from instrumentation and cannot be reduced by increasing the number of measurements, if the instruments and conditions remain unchanged. If the systematic error has a known value, this value should be added to or subtracted from the result of the measurement, and error due to this source should be considered zero. Systematic error should be eliminated by correcting, properly adjusting or changing the instrument, and/or by changing the flow conditions, for example, the length of straight approach channel of a stream-gauging section. These errors are often due to difficult measuring conditions, such as unsteady flow, meandering and bad location of stations.

Random errors cannot be eliminated, but their effects can be reduced by repeated measurements of the element. The uncertainty of the arithmetic mean computed from n independent measurements is several times smaller than the uncertainty of a single measurement. The distribution of random errors can usually be assumed to be normal (Gaussian). For certain cases, normal distribution can or should be replaced by other statistical distributions.

2.3.3.4 Sources of error

Each instrument and measuring method has its own sources of error. Therefore, it would be difficult to list all possible sources of error. The specific sources are usually mentioned in the descriptions of the design of the instruments and operating procedures, such as those in ISO Standards, and the *Manual on Stream Gauging* (WMO-No. 519). Some typical sources of error include:

(a) Datum or zero error originates from the incorrect determination of the reference point of an instrument, for example, staff-gauge zero level, difference between the staff-gauge zero and the weir-crest levels;
(b) Reading error results from the incorrect reading of the indication by the measuring instrument, for example, due to bad visibility, waves, or ice at the staff gauge;
(c) Interpolation error is due to inexact evaluation of the position of the index with reference to the two adjoining scale marks between which the index is located;
(d) Observation error is similar to the reading error and is attributed to neglect or incompetence of the observer;
(e) Error due to the negligence of one or several variables needed to determine the measured value (for example, assuming a unique stage-discharge relationship during periods of unsteady flow when slope as well as stage is a significant determinant of discharge);
(f) Hysteresis (definition under 2.3.3.2);
(g) Non-linearity error is that part of error whereby a change of indication or response departs from proportionality to the corresponding change of the value of the measured quantity over a defined range;
(h) Insensitivity error arises when the instrument cannot sense the given change in the measured element;
(i) Drift error is due to the property of the instrument in which its measurement properties change with time under defined conditions of use, for example, mechanical clockworks drift with time or temperature;
(j) Instability error results from the inability of an instrument to maintain certain specified metrological properties constant;
(k) Out-of-range error is due to the use of an instrument beyond its effective measuring range, lower than the minimum or higher than the maximum value of the quantity, for which the instrument/installation has been constructed, adjusted, or set (for example, unexpected high water level);
(l) Out-of-accuracy class error is due to the improper use of an instrument when the minimum error is more than the tolerance for the measurement.

2.3.3.5 Secondary errors of measurement

Hydrological observations are often computed from several measured components. For example, discharge at measuring structures is computed as a function of a discharge coefficient, characteristic dimensions and head. For estimating the resultant uncertainty, the Gauss error transfer (propagation) theory can be applied.

Resultant uncertainty is often referred to as overall uncertainty, which can be calculated from the uncertainties of the individual components if the errors of the individual components are assumed to be statistically independent.

If a quantity, Q, is a function of several measured quantities, x, y and z, the resultant uncertainty, e_Q, in Q due to uncertainties, e_x, e_y and e_z, in x, y and z, respectively, should be evaluated by the simplified equation of the transfer (propagation):

$$(e_Q)^2 = \left(\frac{\partial_Q}{\partial x} e_x\right)^2 + \left(\frac{\partial_Q}{\partial y} e_y\right)^2 + \left(\frac{\partial_Q}{\partial z}\right)^2 \qquad (2.6)$$

where ∂_Q/∂_x, ∂_Q/∂_y and ∂_Q/∂_z are the partial differentials of the function expressing explicitly the relationship of the dependent variable with the independent variables.

In hydrological measurements, it is very rare that a measurement can be repeated under the same conditions in the field. The standard deviation should therefore be determined by using data of changing variables as in the case of a discharge rating curve.

The standard error of estimate:

$$s_e = \left(\frac{\sum d^2}{n-2} \right)^{1/2} \tag{2.7}$$

of the mean of observations is extremely important for characterizing the stage-discharge relationship, which needs special treatment because the relationship is not linear, but approximately logarithmic. It is an estimate of the accuracy of the computed mean relationship in a regression and, therefore, it is the range within which the true mean would be expected to lie (Figure I.2.4).

For small samples, it could be useful to have a corrected standard error of estimate, obtained by multiplying s_e by $\left(\frac{n}{n-2}\right)^{1/2}$, resulting as:

$$s_{mr} = \frac{s_e}{\sqrt{n}} \tag{2.8}$$

2.3.3.6 Characterization of instruments and methods of observation

The accuracy of a measuring instrument can be characterized by an uncertainty at a given value, corresponding to a maximum or minimum measurable value. The accuracy of an instrument without a reference value can be misunderstood or misinterpreted. The instrument accuracy is in many cases only one component of the overall accuracy of the measurement.

For characterization of uncertainty, the 95 per cent confidence level is commonly used. That is, in 5 per cent of the cases, the error could be outside the stated confidence interval. According to the *Technical Regulations* (WMO-No. 49), Volume III, measurement uncertainties should be reported in one of the following forms:

(a) Uncertainties expressed in absolute terms: Measured value of hydrological elements, for example, discharge: Q = ...
Random uncertainty: $(e_r)_{95}$ = ...

(b) Uncertainties expressed in percentage terms: Measured value of the hydrological elements Q = ...
Random percentage uncertainty $(e_r)_{95\%}$= ...%

In practice, uncertainties of measurements are given in a form where uncertainty is expressed as a ratio (or percentage) of Q_m, the measured value. For example, in the case of $(e_r)_{95}$ = 10%, $Q_m \pm 0.10\, Q_m$ will contain the true value of Q 95 per cent of the time. In this case, the uncertainty is formulated by assuming average measurement conditions.

2.3.3.7 Recommended accuracy of hydrological measurements

The recommended accuracy depends mainly on the anticipated use of the measured data (the purpose of the measurement), on the potentially available instruments and on the available financial resources. Therefore, it cannot be a constant value. Rather it should be a flexible range. The recommended accuracy levels are tabulated in Table I.2.5 as a general guidance for instruments and methods of observation. In many countries, national standards regulate the required accuracies.

2.3.4 Calibration of instruments

One of the major sources of error, as stated above, is due to change in measurement characteristics of the instruments. Hydrological instrumentation comprises a large variety of mechanical, electromechanical and electronic devices. Mechanical instruments such as current meters or anemometers provided by reputable manufacturers are made with precision dies and are usually supplied with a factory calibration table. The factory calibration will, of course, only apply if the instrument is not damaged in use and is properly maintained. Many national hydrological agencies operate facilities to verify factory calibrations and international standards for the manufacture and calibration of, for example, current meters.

Increasingly, there is a trend towards replacing mechanical devices with electronic ones. Although they are more reliable than mechanical devices, they usually are not repairable in the field and must simply be substituted for a replacement device. Electronic instrumentation poses particular problems for hydrological agencies that may be making a transition from electromechanical devices to electronic ones as the calibration issues may be quite different. Calibration of an electronic instrument may drift due to temperature or pressure changes, or solid-state sensors may become fouled during use. It is essential that instruments be designed to function in the range of conditions that are likely to occur at the data-collection site. Some instruments have built-in calibration checks and it is important that these be used.

Table I.2.5. Recommended accuracy (uncertainty levels) expressed at the 95 per cent confidence interval

Precipitation (amount and form)	3–7%
Rainfall intensity	1 mm h^{-1}
Snow depth (point)	1 cm below 20 cm or 10% above 20 cm
Water content of snow	2.5–10%
Evaporation (point)	2–5%, 0.5 mm
Wind speed	0.5 m s^{-1}
Water level	10–20 min
Wave height	10%
Water depth	0.1 m, 2%
Width of water surface	0.5%
Velocity of flow	2–5%
Discharge	5%
Suspended sediment concentration	10%
Suspended sediment transport	10%
Bed-load transport	25%
Water temperature	0.1–0.5°C
Dissolved oxygen (water temperature is more than 10°C)	3%
Turbidity	5–10%
Colour	5%
pH	0.05–0.1 pH unit
Electrical conductivity	5%
Ice thickness	1–2 cm, 5%
Ice coverage	5% for ≥ 20 kg m^{-3}
Soil moisture	1 kg m^{-3} ≥ 20 kg m^{-3}

Notes:

1. When a range of accuracy levels is recommended, the lower value is applicable to measurements under relatively good conditions and the higher value is applicable to measurements under difficult situations.
2. Obtaining the recommended accuracy of precipitation measurements, 3–7 per cent, will depend on many factors, including gauge characteristics. For gauges having their orifice above the ground, the gauge catch deficiency is strongly determined by wind speed and precipitation type. The catch deficiency for light snow falling during strong wind can for example be 50 per cent or more.

2.4 DESIGN AND EVALUATION OF HYDROLOGICAL NETWORKS

2.4.1 General concepts of network design

A hydrological data network is a group of data-collection activities that is designed and operated to address a single objective or a set of compatible objectives. Frequently, the objectives are associated with a particular use that is anticipated for the data being collected in the network – for example, for a water resources assessment, a development plan, or a project design. A particular hydrological station or gauge may be included in more than one network if its data are being used for more than one purpose. In most parts of the world this is more commonly the case than not. Alternatively, a single network may consist of several types of station or gauge if they are all contributing information to the network's objective. For example, both raingauges and stream gauges might be included in a flood forecasting network.

The term network is frequently used in a less rigorous sense. It is often possible to hear of surface-water network, groundwater network, precipitation network, or water-quality network when the speaker is referring to an aggregation of gauges and stations that have no coherence in their objectives. Data-collection sites included in a network under this looser definition may even have disparate uses for the data being collected. This disparity of usage is more than just a semantical oddity. It can cause confusion and false expectations when network analysis and design are being discussed among programme managers and hydrologists.

A network design could be based on a maximization of the economic worth of the data that are to be collected. However, such is not the case in the real world. Generally, in water resources decision-making, the economic impacts of hydrological data are never considered. Decisions are made based on the available data; the option of delaying the decision to collect more data is not explored, or deemed unacceptable. However, several examples of exceptions to this general rule are contained in the *Cost–benefit Assessment Techniques and User Requirements for Hydrological Data* (WMO-No. 717) and in the *Proceedings of the Technical Conference on the Economic and Social Benefits of Meteorological and Hydrological Services* (WMO-No. 733). A review of the hydrometric network in one Canadian province indicated that the cost–benefit ratio of the existing provincial network was 19 and that the network could be tripled in size to maximize economic benefits (Azar and others, 2003). Even in nations with very dense hydrometric networks, such as the United Kingdom, economic analysis inevitably demonstrates that benefits of hydrometric networks exceed the cost (CNS, 1991). Nonetheless many countries suffered considerable reductions in their hydrological networks in the 1980s and 1990s as a consequence of budget reductions for monitoring agencies (Pearson, 1998). For example, network reductions in Canada, Finland, New Zealand and the United States of America were 21, 7, 20 and 6 per cent, respectively. Network reductions, with rare exceptions such as New Zealand, continue.

In lieu of complete economic analyses, network designs are usually based on surrogate measures of the economics or on guidance such as that presented subsequently in this chapter.

2.4.1.1 Definition of network design

A complete network design answers the following questions pertaining to the collection of hydrological data:

(a) What hydrological variables need to be observed?
(b) Where do they need to be observed?
(c) How often do they need to be observed?
(d) What is the duration of the observation programme?
(e) How accurate should the observations be?

To answer these questions, network design can be conceptualized as a pyramid, as shown in Figure I.2.5. The base of the pyramid is the science of hydrology. Without a thorough understanding of the hydrological setting of the area in which the network is to be established, there is little chance that the resulting network will generate information in an effective manner. Hydrological understanding comes from both education and experience, but there is no substitute for experience when initiating a hydrological network in an area where little or no historical data are available.

The right-hand side of the pyramid deals with quantitative methods for coping with hydrological uncertainty. Because of measurement errors and errors caused by sampling in space and time, there will always be hydrological uncertainty. Perfect hydrological information can never exist. Probabilistic descriptions of these errors are the most effective means of dealing with the resulting uncertainty. Probability theory provides the theorems and the language for doing so and also yields the understanding that is necessary for appropriate use of the tools of statistics. In Figure I.2.5, statistical tools are represented by sampling theory and by correlation and regression analyses, which are commonly used in quantitative network-design approaches. However, there are many other branches of statistics that may be found useful in network analysis and design. The capstone of uncertainty is Bayesian analysis, which pertains to the level of uncertainty in the descriptions of

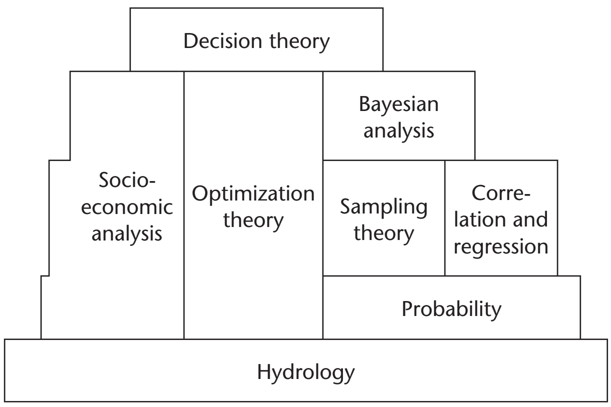


Figure I.2.5. The basic building blocks of network design

hydrological uncertainty. In other words, the probabilistic descriptions of uncertainty, based on statistics of finite samples of hydrological data, are uncertain in themselves. Reduction of uncertainty about uncertainty is a key aspect of taking full advantage of the information contained in the data that the network will generate.

The column in the middle of the structure, labelled optimization theory, is often included taxonomically as a part of socio-economic analysis. However, even in the absence of socio-economics, the optimization theory is often used in hydrological network design. Thus, it is included here as a separate component of the structure. A suite of mathematical programmes, each with its own utility and shortcomings, comprises optimization theory, which is often referred to as operations research. The context of the network-design problem determines which, if any, of the mathematical programmes can be used in a given situation. Often, the choice between two or more network designs must be made on the basis of judgement because appropriate optimization tools either do not exist or are too consuming of computer resources to be efficient.

Atop the pyramid is decision theory, which is a formal mechanism for integrating all of the underlying components. The application of decision theory in network design is not required – it is not even possible in most circumstances. However, an understanding of its pretexts and premises can make a network designer more cognizant of the impacts of his or her final decisions.

The left-hand side of the pyramid represents a rather amorphous group of technologies under the heading of socio-economic analysis. In addition to social sciences and economics, this part of the network-design structure also encompasses policy science and even politics. The latter plays a very important role in the realization of the potential benefits of water and, thus, also in the ultimate value of the data from the network. The left-hand side of the structure is the part that usually receives little rigorous consideration in the design of the data network. This is probably attributable to two causes: the subject matter is difficult to treat in an objective, mathematical way; and to do so in a substantive manner requires the synthesis of inputs from many disciplines beyond those of hydrology and water resources engineering. Thus, a network design that includes a significant socio-economic analysis will probably be both expensive and time-consuming.

Nevertheless, hydrological data-collection sites are often installed to meet pressing social needs and economic constraints with relatively little thought to meeting long-term hydrological information needs. Aside from meeting scientific needs, data-collection sites may be installed to assist water mangers in responding to extreme events such as floods or droughts, allocating water supplies among competing uses, or meeting regulatory requirements. Sites operated for these latter purposes may also lead to increased hydrological understanding, but the resulting network is by no means optimized for that purpose.

2.4.1.2 Surrogate approaches

Since full-scale and complete network design is either impossible or impractical in today's world, approaches that substitute surrogate measures, objectives, or criteria are actually used to answer the questions that comprise network design. For example, a common substitution is to maximize information content from a network in lieu of optimizing the economic value of the data. Studies have shown that, if information is used properly, it can be expected to contribute to the economic worth resulting from a decision. The more information, the better the decision. However, the economic impact of information is not linearly related to its magnitude and the marginal worth of additional information decreases with the amount of information that is available. Thus, the use of this surrogate criterion can lead a Hydrological Service in the right direction if only sparse hydrological information is available, but its use can cause the collection of excess data if the region of interest already has a reasonably adequate information base.

Among the basic analytical techniques that take advantage of surrogates in the design of networks are cartographic analysis, correlation and regression methods, probabilistic modelling, deterministic modelling and regionalization techniques. Each method has particular applications and the choice depends on the limitations of available data and the type of problem under consideration. Quite often the different techniques are combined in certain applications. The *Casebook on Hydrological Network Design Practice* (WMO-No. 324) presents applications of these techniques as a means of determining network requirements. Further examples are contained in other publications (WMO/IHD Project Report No. 12; WMO-Nos. 433, 580, 806).

2.4.1.3 The basic network

The worth of the data that derive from a network is a function of the subsequent uses that are made of them. Nevertheless, many of the uses of hydrological data are not apparent at the time of the network design and, therefore, cannot be used to justify the collection of specific data that ultimately may be of great value. In fact, few hydrological data would be collected if a priori economic justifications were required. However, modern societies have developed a sense that information is a commodity that, like insurance, should be purchased for protection against an uncertain future. Such an investment in the case of hydrological data is the basic network, which is established to provide hydrological information for unanticipated future water resources decisions. The basic network should provide a level of hydrological information at any location within its region of applicability that would preclude any gross mistakes in water resources decision-making. To accomplish this aim, at least three criteria must be fulfilled:

(a) A mechanism must be available to transfer the hydrological information from the sites at which the data are collected to any other site in the area;
(b) A means for estimating the amount of hydrological information (or, conversely, uncertainty) at any site must also exist;
(c) The suite of decisions must include the option of collecting more data before the final decision is made.

2.4.1.3.1 *The minimum network*

In the early stages of development of a hydrological network, the first step should be the establishment of a minimum network. Such a network should be composed of the minimum number of stations which the collective experience of hydrological agencies of many countries has indicated to be necessary to initiate planning for the economic development of the water resources.

The minimum network is one that will avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development of the country. It should be developed as rapidly as possible by incorporating existing stations as appropriate. In other words, this pragmatic network will provide the basic framework for network expansion to meet future needs for specific purposes. It is emphasized that a minimum network will not be adequate for the formulation of detailed development plans and will not meet the numerous requirements of a developed region for the operation of projects and the management of water resources.

2.4.1.3.2 *Expanding the information base*

Once the minimum network is operational, regionalized hydrological relationships, interpreted information and models can be formulated for estimating general hydrological characteristics, including rainfall and runoff at any location in the area. The basic network of observing stations should be adjusted over time until regional hydrological relationships can be developed for ungauged areas that provide the appropriate level of information. In most cases, this adjustment will result in increases in the densities of hydrological stations. However, this is not always the case. Since models are used to transfer the information from the gauged to the ungauged sites, the quality of the model is also a factor in determining the density of the basic network. If a model is particularly good, it can distil the information from the existing data better than a poorer model, and the better model would require less data to attain a given level of regional information than would the poorer one. In an extreme situation, the regional model might be so good that the level of data collection in the basic network could be reduced.

Owing to the broad dependence on the stations in the basic network, it is very important that the records from all of these stations be of high quality. Even if the installation of a station is adequate, its records may be of little value if it is not operated correctly. Continuous operation may be difficult – especially over a period of 20 years or more. A minimum network, in which stations are abandoned or irregularly observed, will have its effective density reduced and is, therefore, no longer an adequate minimum network. For that reason, care should be taken not only in establishing, but also in providing for, the continuing operation of these stations and for monitoring the reliability and accuracy of the collected records.

Economic as well as technical considerations are involved in the design and implementation of basic networks, and the number of stations requiring observation over an indefinitely long period cannot be excessive. Consequently, a sampling procedure may be adopted to maximize the cost-effectiveness of the basic network. One such approach categorizes the stations as either principal or base stations, or secondary stations. The secondary stations are operated only long enough to establish a stable relationship, usually by means of correlations, with one or more of the base stations. A new secondary station can then be established with the equipment and funds that had been in use at the discontinued site. Records can be reconstructed at the discontinued site by means of the base-station records and the inter-station relationship. At times, it may be necessary to re-establish secondary stations if it is believed that the conditions either at the secondary site or at its related base station(s) have changed. The perpetual nature of the principal stations in the basic network provides a basis for monitoring long-term trends in hydrological conditions in the region. This is particularly important in the light of potential changes in the hydrological cycle that could be caused by land-use changes or by increases in stratospheric greenhouse gases.

2.4.1.4 Integrated network design

The hydrological cycle is a continuum, and its interconnections permit the partial transfer of information obtained in one part of the cycle to another. The efficiency of such transfers is proportional to the degree of hydrological understanding that is captured in the models that are used to route the water (and the information) between the parts of the cycle. For example, precipitation records on or near a gauged drainage basin permit the reconstruction of streamflow records during periods when the stream-gauge malfunctions if a valid precipitation-runoff model has been calibrated during times when all gauges were functioning properly. A groundwater observation well may perform a similar role for malfunctions of the stream gauge if the well is monitoring the water table of an aquifer that is directly connected to the stream.

To date, little has been done to include these interactions in network designs in an explicit manner. Ideally, the complementarity between the raingauges and the stream gauges that are operated in a flood-forecasting network could be used in designing a network for water resources assessment, for example. If the economic trade-offs between the two networks could be defined, they could be optimized together and peak efficiencies in information generation could be attained for both. In spite of this technological shortcoming, networks should be designed iteratively, and the outcomes of an existing design should become starting points for subsequent designs. By extension of the above example, this can be illustrated. The flood-forecasting network will probably have stream gauges and precipitation gauges at rather specific locations to meet its information needs. As the water resources assessment will generally have less specific requirements for its information sources, it will be likely that many of the gauges of the flood-forecasting network can be incorporated into the assessment network and used as initial given conditions for its design. This iterative approach is particularly useful when designing generalized networks, like the basic network on the basis of networks, with more restrictive information demands. Networks with more restrictive demands include benchmark stations, representative basins and networks for operational purposes.

2.4.1.4.1 *Stations for operational purposes*

Stations may be established for such specific purposes as reservoir operation, irrigation, navigation, water-quality monitoring or flood forecasting. Benchmark or reference stations would also belong to this category. The length of operation of special stations is related to the purpose for which they were installed.

In some cases, the specific purpose to be served may require observations on only one particular aspect of an element, or be confined to one season of the year. For example, a hydrometric station may consist of a crest gauge for recording only the maximum flood peak or a storage gauge for measuring the total precipitation during a season. Although such stations may perform a valuable function, they do not provide the data required for general hydrological analyses. Consequently, such stations may or may not be included in a basic hydrological network.

2.4.1.4.2 *Benchmark stations*

Each country and each natural region of large countries should contain one benchmark station to provide a continuing series of consistent observations on hydrological and related climatological variables. Hydrological benchmark stations should be established in areas that are relatively uninfluenced by past or future anthropogenic changes. Since long records are the essence of a benchmark station, consideration should be given to existing stations if they meet the other requirements. The Reference Hydrometric Basin Network of Canada is one such example (Harvey and others, 1999). Climatological benchmark stations are known as reference stations.

2.4.1.4.3 *Representative basins*

A representative basin is desirable in each natural region – especially in those regions where great economic growth is expected or where the hydrological problems are particularly difficult. In their simplest form, they permit the simultaneous study of precipitation and runoff, thus helping to make up for deficiencies in short periods of observation and low densities of minimum networks.

2.4.1.4.4 *Project stations*

These are stations established for a limited span of time, for specific purposes, often research oriented. Other frequent objectives may be investigations before or after physical interventions in the catchment, or for supplementing the regional coverage of the basic network. Project stations are characterized by:
(a) Limited lifetime;
(b) Data quality depending on purpose.

2.4.1.5 Conducting a network analysis

Figure I.2.6 lays out the steps that should be taken in conducting a review and redesign of an existing hydrological network. Such reviews should be conducted periodically to take advantage of the reduction in hydrological uncertainty brought about by the added data since the last network analysis and to tune the network to any changes in the socio-economic environment that may have transpired. The steps of the analysis are discussed individually below.

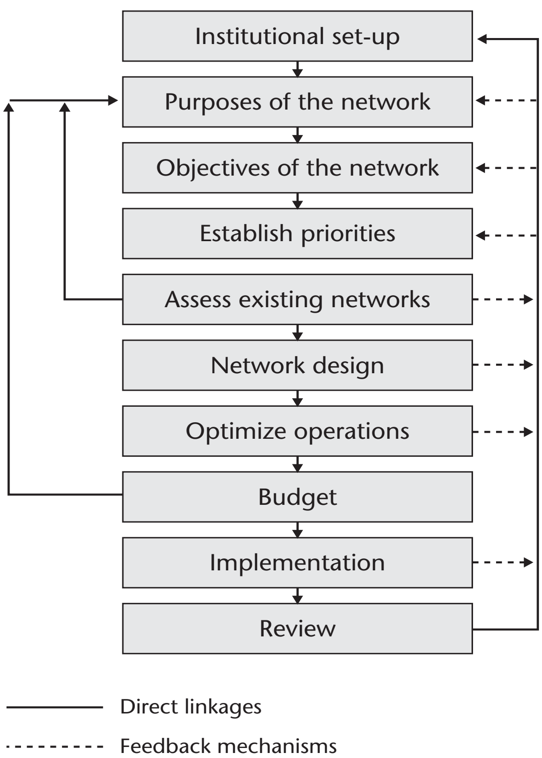


Figure I.2.6. A framework for network analysis and redesign

Institutional set-up

The roles and aims of all of the organizations involved in various aspects of water resources management should be defined and identified, particularly legislative responsibilities. Communication links between these organizations should be improved to ensure coordination and integration of data-collection networks.

Purposes of the network

The purposes of the network in terms of the users and uses of the data should be identified. Data users and uses can vary temporally and spatially. There is also a need to identify potential future needs and incorporate these into the design as well.

Objectives of the network

Based on the purpose of the network, an objective or set of objectives can be established in terms of the information required. An indication of the consequences of not being able to provide this information may prove useful later.

Establish priorities

If there is more than one objective, priorities need to be set for later evaluation. If all objectives can be met within the budget, then this is not needed. However, if they cannot be met, then the lower-priority objectives may not be met fully.

Assess existing networks

Information on the existing networks should be compiled and interpreted to determine if the current networks fulfil the objectives. This may include comparisons with other basins and/or networks.

Network design

Depending on the available information and the objectives defined, the most appropriate network-design technique or techniques should be applied. This may be simple hydrological characteristics, regression relationships, or more complex network analysis using generalized least squares methods.

Optimize operations

Operational procedures account for a significant portion of the cost of data collection. This includes the types of instrument, frequency of station visits and structure of field trips. The minimum-cost operational procedures should be adopted.

Budget

Based on the identified network and operational procedures, the cost of the operation of the network can be established. If this is within the budget, the next step can be followed. If not, either additional funding must be obtained or the objectives and/or priorities need to be examined to determine where costs may be reduced. The process adopted should allow the designer to express the impact of insufficient funding in terms of not meeting objectives or reduced information and net impacts.

Implementation

The redesigned network needs to be implemented in a planned manner. This will include both short- and long-term planning horizons.

Review

Since a number of the above components are variable in time, a review can be required at the instigation of any particular component – for example, changes in users or uses, or changes in the budget. To be ready to meet such changes, a continuous review process is essential.

2.4.2 Density of stations for a network

The concept of network density is intended to serve as a general guideline if specific guidance is lacking. As such, the design densities must be adjusted to reflect actual socio-economic and physio-climatic conditions. Computer-based mathematical analysis techniques should also be applied, where data are available, to optimize the network density required to satisfy specific needs.

As stated in 2.4.1.3.1, the minimum network is one that will avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development and environmental needs of the country. It should be developed as rapidly as possible, incorporating existing stations, as appropriate. In other words, such a network will provide the framework for expansion to meet the information needs of specific water uses.

In the following sections, minimum densities of various types of hydrological stations are recommended for different climatic and geographic zones. These recommendations are based on the 1991 review of Members' responses regarding the WMO basic network assessment project (WMO/TD-No. 671) and are presented in Table I.2.6. However, these recommended network densities are being revisited through a study undertaken by the Commission for Hydrology and the revised recommended densities will be placed on the Website as part of the electronic version of the Guide.

It is impossible to define a sufficient number of zones to represent the complete variety of hydrological conditions. The simplest and most precise criterion for the classification of zones would be on the basis of the areal and seasonal variation of rainfall. Each country could present a good map of annual precipitation and a minimum network could be developed from this. However, this would

Table I.2.6. Recommended minimum densities of stations (area in km^2 per station)

Physiographic unit	*Precipitation*		*Evaporation*	*Streamflow*	*Sediments*	*Water quality*
	Non-recording	*Recording*				
Coastal	900	9 000	50 000	2 750	18 300	55 000
Mountains	250	2 500	50 000	1 000	6 700	20 000
Interior plains	575	5 750	5 000	1 875	12 500	37 500
Hilly/undulating	575	5 750	50 000	1 875	12 500	47 500
Small islands	25	250	50 000	300	2 000	6 000
Urban areas	–	10–20	–	–	–	–
Polar/arid	10 000	100 000	100 000	20 000	200 000	200 000

not help countries that need a network most as they have very few prior records, and the establishment of a good precipitation map is not possible. Also, the countries with very irregular rainfall distribution need to be considered as a special category. In such cases, it is not advisable to base the classification on this one characteristic.

Population density also affects network design. It is almost impossible to install and operate, in a satisfactory manner, a number of stations where population is sparse unless the stations are highly automated. Sparsely settled zones, in general, coincide with various climatic extremes, such as arid regions, polar regions or tropical forests.

At the other extreme, densely-populated urban areas need a very dense raingauge network for both temporal and spatial resolution of storms and for design, management and real-time control of the storm-drainage systems and for other engineering applications.

From these considerations, a limited number of larger zones have been defined for the definition of density norms in a somewhat arbitrary manner adopting some general rules. Six types of physiographic regions have been defined for minimum networks:
(a) Coastal;
(b) Mountainous;
(c) Interior plains;
(d) Hilly/undulating;
(e) Small islands (surface areas less than 500 km^2);
(f) Polar/arid.

For the last type of region, it is necessary to group the areas in which it does not seem currently possible to achieve completely acceptable densities because of sparse population, poor development of communications facilities, or for other economic reasons.

2.4.2.1 Climatological stations

The following types of data are collected at a climatological station in the basic network: precipitation, snow survey and evaporation. It is understood here that evaporation or snow-measuring stations, particularly the former, will generally measure temperature, humidity and wind because these meteorological elements affect evaporation and melting.

2.4.2.1.1 *Precipitation stations*

If one follows certain principles of installation and use, the small number of stations in the minimum network can furnish the most immediate needs. In general, precipitation gauges should be as uniformly distributed as is consistent with practical needs for data and the location of volunteer observers. In mountainous regions, attention must be given to vertical zonality by using storage gauges to measure precipitation at high altitudes. Precipitation gauges may be designed specifically to measure snow-water equivalent, either through the addition of shielding to reduce under-catch due to wind or through the use of pressure sensors. Periodic manual snow surveys may be used to supplement the network, but they should not be counted as part of the network.

The network should consist of three kinds of gauge:
(a) Standard gauges – These gauges are read daily for quantity. In addition to daily depth of precipitation, observations of snowfall, the depth of snow on the ground and the state of the weather are to be made at each standard precipitation station;
(b) Recorders – In developing networks, it is advisable to aim to have at least 10 per cent of such stations. The greatest density of recording stations should be achieved in those areas subject to intense, short-duration rainfalls. Such stations will provide valuable information on the intensity, distribution, and duration of precipitation.
    For urban areas where the time resolution needed for rainfall measurements is of the order of one to two minutes, special attention should be paid to the time synchronization of the raingauges. For reliable measurements, tipping-bucket raingauges with an electronic memory (or another computer readable medium) are recommended.
    In assigning priorities to locations for recording-raingauge installations, the following types of areas should be given priority: urban areas (population in excess of 10 000) where extensive drainage systems are likely to be constructed, river basins in which major river control systems are anticipated or are in operation, large areas inadequately covered by the existing network and special research projects;
(c) Storage gauges (totalizers) – In sparsely settled or remote regions, such as in desert or mountainous terrain, storage gauges may be used. These gauges are read monthly, seasonally, or whenever it is possible to inspect the stations.

Location of precipitation gauges relative to streamgauging stations – To ensure that precipitation data are available for extending streamflow records, flood-forecasting purposes or hydrological analysis, coordination of the locations of the precipitation gauges with respect to those of the stream gauges is of great importance. Precipitation gauges should be located so that basin precipitation can be estimated for each stream-gauging station. These will usually be located at or near the stream gauge and in the upper part of the gauged drainage basin. A precipitation gauge should be located at the site of the stream gauge only if the observations will be representative of the general area. There can be cases in which it is desirable to locate the precipitation gauge some distance away from the stream gauge, as for instance when the stream gauge is in a narrow, deep valley.

2.4.2.1.2 *Snow surveys*

Where applicable, observations of snowfall, water equivalent of snow and depth of snow on the ground should be made at all precipitation stations in the minimum network.

The water equivalent of snow at the time of maximum accumulation is an indication of total seasonal precipitation in regions where winter thaws and winter snow melt are insignificant. In such regions, surveys of the snow cover on selected courses may be useful in estimating seasonal precipitation at points where the normal observations are unavailable. Such snow-cover surveys will also provide useful information for river forecasting and flood studies.

Snow-cover surveys are conducted by personnel equipped for sampling the accumulated snow and for determining its depth and water equivalent (3.5). The number of snow courses and their location and length will depend upon the topography of the catchments and the purposes for which the data are being collected. The full range of elevation and the types of exposure and vegetation cover in the area of interest should be considered in selecting representative courses. It is suggested that one course for 2000 to 3000 km^2 is a reasonably good density for less homogeneous regions, and one course for 5000 km^2 in homogeneous and plain areas. However, each case must be considered on its own merits, and these generalities must not be applied indiscriminately.

In the early stages of network development, snow-cover surveys will usually be made only once a year, near the expected time of maximum accumulation. It will be desirable, later on, to extend the operation to include surveys at regular intervals throughout the snowfall season. As soon as it becomes feasible, these periodic snow surveys should be augmented by regular measurements of snow precipitation and observations of related meteorological factors, such as radiation, soil temperature and wind velocity.

2.4.2.1.3 *Evaporation stations*

Evaporation can be estimated indirectly in the water-budget, energy-budget and aerodynamic approaches, by extrapolation from pan measurements or directly through use of eddy-correlation equipment (Chapter 4). An evaporation station consists of a pan of standard national design where daily observations of evaporation are made, together with daily observations of precipitation, maximum and minimum water and air temperatures, wind movement and relative humidity or dewpoint temperature.

Evaporation plays an important role for long-term studies of the water regime of lakes and reservoirs and for water management. In such cases, the number and distribution of evaporation stations are determined according to the area and configuration of the lakes and the climatic region or regions involved.

2.4.2.2 Hydrometric stations

2.4.2.2.1 *Streamflow stations*

The main objective of the stream-gauging network is to obtain information on the availability of surface-water resources, their geographical distribution and their variability in time. Magnitude and frequency of floods and droughts are of particular importance in this regard.

In general, a sufficient number of streamflow stations should be established along the main stems of large streams to permit interpolation of discharge between the stations. The specific location of these stations should be governed by topographic and climatic considerations. If the difference in flow between two points on the same river is not greater than the limit of error of measurement at the station, then an additional station is unjustified. In this context, it must also be stressed that the discharge of a small tributary cannot be determined accurately by subtracting the flows at two main stream-gauging stations that bracket the mouth of the tributary. Where the tributary flow is of special interest in such a case, a station on the tributary will be required. It will usually take its place as a secondary station in the minimum network. The streamflow stations may be interspersed with stage stations (2.4.2.2.2).

Wherever possible, the base stations should be located on streams with natural regimes. Where this is impractical, it may be necessary to establish additional stations on canals or reservoirs to obtain the necessary data to reconstruct the natural flows at the base stations. Computed flows past hydroelectric plants or control dams may be useful for this purpose, but provisions will have to be made for calibration of the control structures and turbines and for the periodic checking of such calibrations during the life of the plants.

Stations should be located on the lower reaches of the major rivers of the country, immediately above the river mouths (usually above tidal influence) or where the rivers cross borders. Stations should also be located where rivers issue from mountains and above the points of withdrawal for irrigation water. Other hydrometric stations are situated at locations, such as where the discharge varies to a considerable extent, below the points of entry of the major tributaries, at the outlets from lakes, and where large structures are likely to be built. Hydrometric stations are often established at major cities to meet a number of societal needs.

To ensure adequate sampling, there should be at least as many gauging stations on small streams as on the main streams. However, a sampling procedure for small streams becomes necessary, as it is impracticable to establish gauging stations on all of them. The discharge of small rivers is strongly influenced by local factors. In highly developed regions, where even the smallest watercourses are economically important, network deficiencies are keenly felt even on streams draining areas as small as 10 km^2.

Stations should be installed to gauge the runoff in different geologic and topographic environments. Because runoff varies greatly with elevation in mountains, the basic network stations must be located in such a way that they can, more or less evenly, serve all parts of a mountainous area, from the foothills to the higher regions. Account should be taken of the varying exposure of slopes, which is of great significance in rough terrain, and to land cover, which may vary with exposure and other factors. Similarly, consideration should be given to stations in districts containing numerous lakes, the influence of which can be determined only through the installation of additional stations.

2.4.2.2.2 *River stages*

Stage (height of water surface) is observed at all stream-gauging stations to determine discharge. There are places where additional observations of water level only are needed as part of a minimum network:

(a) At all major cities along rivers, river stages are used for flood forecasting, water supply and transportation purposes;
(b) On major rivers, at points between stream-gauging stations, records of river stage may be used for flood routing and forecasting purposes.

2.4.2.2.3 *Lake and reservoir stages*

Stage, temperature, surge, salinity, ice formation, etc., should be observed at lake and reservoir stations. Stations should be established on lakes and reservoirs with surface areas greater than 100 km^2. As in the case of rivers, the network should sample some smaller lakes and reservoirs as well.

2.4.2.2.4 *Sediment discharge and sedimentation*

Sediment stations may be designed either to measure total sediment discharge to the ocean or to measure the erosion, transport and deposition of sediment within a country, basin, etc. In designing a minimum network, emphasis should be placed on erosion, transport and deposition of sediment within a country. An optimum network would contain a sediment station at the mouth of each important river discharging into the sea.

Sediment transport by rivers is a major problem in arid regions, particularly in those regions underlain by friable soils and in mountainous regions where, for engineering applications, the amount of sediment loads should be known.

The designer of a basic network must be forewarned that sediment-transport data are much more expensive to collect than other hydrological records. Consequently, great care must be exercised in selecting the number and location of sediment-transport stations. Emphasis should be placed on those areas where erosion is known to be severe. After a few years of experience, it may be desirable to discontinue sediment measurements at those stations where sediment transport no longer appears to be of importance.

Sediment-transport data may be supplemented by surveys of sediment trapped in lakes or reservoirs. Echo-sounding devices are useful for this purpose. However, information obtained in this way is not considered a substitute for sediment-transport measurements at river stations. Sediment discharge measurement and the computation of sediment load are covered in 5.5.

2.4.2.2.5 *Water-quality stations*

The usefulness of a water supply depends, to a large degree, on its chemical quality. Observations of chemical quality, for the purposes of this Guide, consist of periodic sampling of water at stream-gauging stations and analyses of the common chemical constituents. ISO Technical Committee 147 has prepared over 200 international standards pertaining to field sampling for water-quality and analytical methods.

The number of sampling points in a river depends on the hydrology and the water uses. The greater the water-quality fluctuation, the greater the frequency of measurement required. In humid regions, where concentrations of dissolved matter are low, fewer observations are needed than in dry climates, where concentrations, particularly of critical ions such as sodium, may be high.

2.4.2.2.6 *Water temperature*

The temperature of water should be measured and recorded each time a hydrometric station is visited to measure discharge or to obtain a sample of the water. The time of day of the measurement should also be recorded. At stations where daily stage observations are made, temperature observations should also be made daily. These observations, the cost of which is negligible, may provide data which are useful in studies of aquatic life, pollution, ice formation, sources of cooling water for industry, temperature effects on sediment transport, solubility of mineral constituents, or climate change.

2.4.2.2.7 *Ice cover on rivers and lakes*

Regular observations of ice cover should include the following:

(a) Visual observations of various processes of ice formation and of ice destruction, with recording of date of first occurrence of floating ice, date of total cover, date of break-up of the ice, and date at which the ice has vanished completely. These observations should be made on a daily basis;
(b) Simultaneous measurement of ice thickness at two or three points near each selected hydrometric station should be made once every 5 to 10 days. The location of measurement points is chosen from detailed surveys of ice cover made at the beginning of the observing period of the stations.

2.4.3 **Specific requirements for water quality**

There are several approaches to water-quality monitoring. Monitoring can be accomplished through a network of strategically located long-term stations, by repeated short-term surveys, or by the most common approach, a combination of the two. In addition to the basic objectives of the programme, the location of stations should take into account the following factors:

(a) Existing water problems and conditions;
(b) Potential growth centres (industrial and municipal);
(c) Population trends;
(d) Climate, geography and geology;
(e) Accessibility;
(f) Available human resources, funding, field and laboratory data handling facilities;
(g) Inter-jurisdictional considerations;
(h) Travel time to the laboratory (for deteriorating samples);
(i) Safety of personnel.

The design of a sampling programme should be tested and assessed during its initial phase to ensure the effectiveness and efficiency with respect to the objectives of the study.

2.4.3.1 **Water-quality parameters**

The parameters that characterize water quality may be classified in several ways, including physical properties (for example, temperature, electrical conductivity, colour and turbidity), inorganic chemical components (for example, dissolved oxygen, chloride, alkalinity, fluoride, phosphorous and metals), organic chemicals (for example, phenols, chlorinated hydrocarbons, polycyclic aromatic hydrocarbons and pesticides), and biological components, both microbiological, such as faecal coliforms, and macrobiotic, such as worms, plankton and fish, which can indicate the ecological health of the aquatic environment.

A second classification is done according to the importance attached to the parameter. This will vary with the type of water body, the intended use of the water and the objectives of the monitoring programme. Water-quality variables are sometimes grouped into two categories:

(a) Basic variables (Table I.2.7) (UNEP, 2005);
(b) Use-related variables:
    (i) Drinking water supplies;
    (ii) Irrigation;
    (iii) General quality for aquatic life.

A third classification that is highly relevant to sampling procedures is done according to stability:
(a) Conservative (does not change materially with time);
(b) Non-conservative (changes with time, but can be stabilized for at least 24 hours by appropriate treatment); or
(c) Non-conservative (changes rapidly with time and cannot be stabilized).

The first two groups can be measured by representative water samples subsequently analysed in the laboratory. The third group needs to be measured in situ.

2.4.3.2 Surface-water quality

Sometimes the programme objectives will precisely define the best locations for sampling in a river or lake system. For example, in order to determine the effect of an effluent discharge on a receiving stream, sampling locations upstream and downstream of the discharge would be required. In other cases, both location and frequency of sampling will be determined by anti-pollution laws or by a requirement for a specific use of a water body. For example, a permit to discharge surface waters may outline details of monitoring, such as location, number of samples, frequency and parameters to analyse. Water-quality monitoring programmes may be

Table I.2.7. GEMS/Water basic variables

Water quality category	*GEMStat parameters*	
Hydrological and sampling variables	Instantaneous discharge	
Physical/Chemical variables	Water discharge/level (GRF) Total suspended solids (R) Temperature pH (GRF)	Electrical conductivity Dissolved oxygen Transparency (L)
Major ions Dissolved salts/Ionic balance	Calcium Magnesium Sodium Potassium Chloride Fluoride (GW)	Sulphate Alkalinity Sum of cations Sum of anions Sodium adsorption ratio
Nutrients	Nitrate plus nitrite Ammonia Organic nitrogen, dissolved Organic nitrogen, particulate	Total phosphorus, dissolved (R, L) Total phosphorus, particulate Total phosphorus, unfiltered (R, L) Silica reactive (R, L)
Organic matter	Organic carbon, dissolved Organic carbon, particulate BOD	COD Chlorophyll *a* (R, L)
Microbiology	Faecal coliform Total coliforms	Giardia Cryptospiridium
Metals Inorganic contaminants (measured as dissolved, particulate, and/or total; particulate concentrations are essential for GRF stations)	Aluminium Arsenic Boron Cadmium Chromium Copper Iron	Lead Manganese Mercury Nickel Selenium Zinc
Organic contaminants	Aldicarb Aldrin Altrazine Benzene 2, 4-D DDTs Dieldrin Lindane	Total hydrocarbons Total chlorinated hydrocarbons Total polyaromatic hydrocarbons PCBs PBDEs (polybrominated diphenyl ethers) Phenols Toxaphene

R Basic variables for river stations only
L Basic variables for lake/reservoir stations only
GW Basic variables for groundwater stations only
R, L Basic variables for river, lake/reservoir stations only
GRF Essential for global river flux monitoring stations

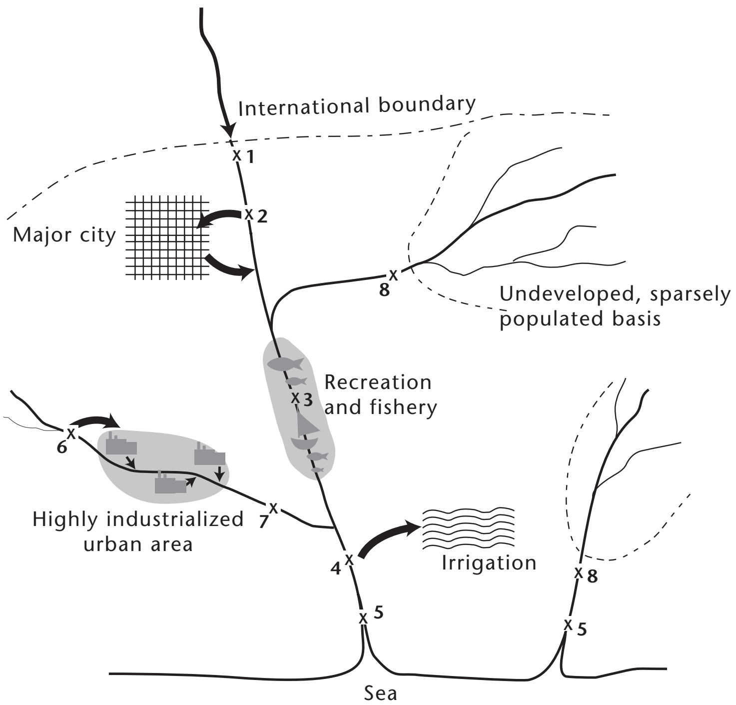
supplemented by intensive, but infrequent, special purpose water-quality surveys aimed at understanding short-term fluctuations in water-quality parameters. As well, special situations may call for water-quality surveillance, the continuous, specific measurement of selected parameters.

Sampling strategies vary for different kinds of water bodies and media, for example, water, sediment, or biota. Rivers mix completely within distances ranging from several kilometres to a few hundred kilometres of any point source of pollution. Lakes may be vertically stratified because of temperature or inflows of high-density saline water. Groundwater tends to flow very slowly, with no surface indication of the changes in its solutes taking place below.

If the objective concerns the impact of human activities on water quality in a given river basin, the basin can be separated into natural and altered regions. The latter can be further subdivided into stationary zones for instance, over periods longer than 10 years, and those in which the impact is variable, such as agricultural, residential and industrial zones. In acid-deposition studies, an important factor is the terrain sensitivity to the deposition. Figures I.2.7 and I.2.8 provide some examples of where and how sampling stations could be located to meet specific objectives on river and lake systems.

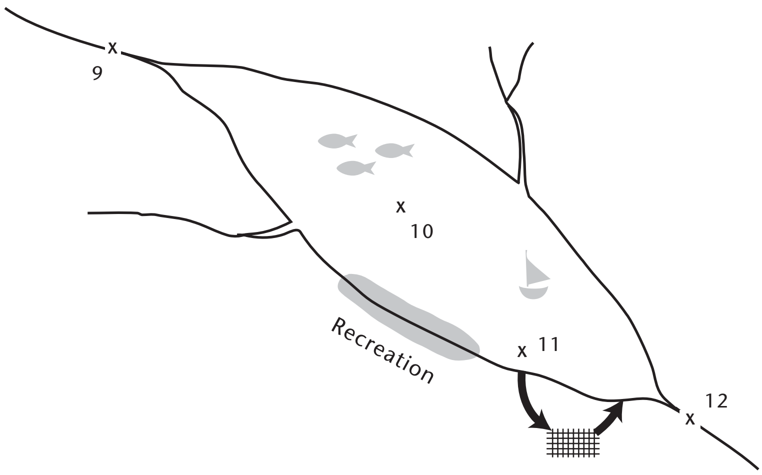
The next step in choosing sampling locations is to collect relevant information about the region to be monitored. The information sought includes geological, hydrological and demographic aspects, as well as the number of lakes and streams, size and locations of aquifers, locations of existing water-quality or stream-gauging stations, flow rates, climatic conditions in the catchment area, historical developments, present and potential municipal and industrial centres, current water intakes and waste outlets, natural salt springs, mine drainage, irrigation schedules, flow regulation (dams), present and planned water uses, stream or lake water-quality objectives or standards, accessibility of potential sampling sites (land ownership, roads and airstrips), availability of services such as electricity, and existing wate-quality data. Figure I.2.9 shows the steps to be followed in selecting sampling sites. The distance downstream to the point of complete mixing is roughly proportional to the stream velocity and to the square of the width of the channel. Rivers are usually sufficiently shallow that vertical homogeneity is quickly attained below a source of pollution. Lateral mixing is usually much more slowly attained. Thus, wide swift-flowing rivers may not be completely mixed for many kilometres downstream from the input point.

Various protocols are recommended to determine representative sampling in the cross-section of the river, for example, six samples analysed in duplicate,



Station	*Criteria*
1	Immediately downstream of an international boundary
2	Diversion for public supply of large town
3	Important fishing, recreation and amenity zone
4	Diversion for large-scale agricultural irrigation
5	Freshwater tidal limit of major river
6	Diversion for large industrial supply
7	Downstream of industrial effluent discharges and important tributary influencing main river
8	Baseline station, water in natural state

Figure I.2.7. Monitoring site: rivers



Station	*Criteria*
9	Principal feeder tributary
10	General water quality of lake
11	Water supply for major city
12	Water leaving lake

Figure I.2.8. Monitoring site: lakes

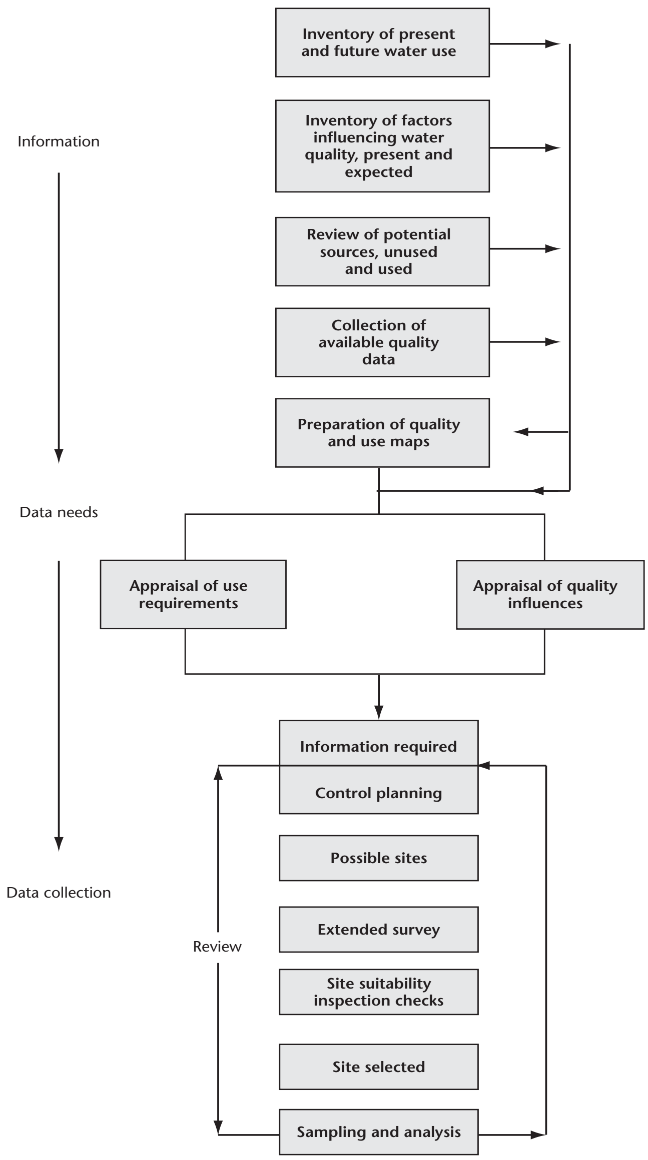


Figure I.2.9. Scheme for the selection of water quality sampling sites

at three positions across the river and two depths or mid-depth samples at the quarter points, or other equal distance points across the width of the river. If a representative sample cannot be obtained, it is advisable to select another site, either immediately upstream or downstream. The other alternative is to obtain a flow-weighted composite sample from samples collected on cross-section verticals.

Longitudinal mixing of irregular or cyclic discharges into a river will have a secondary influence on the location of a sampling site. Their effects need to be taken into account in deciding the frequency of sampling and interpreting data.

Sampling frequency depends on the purpose of the network, the relative importance of the sampling station, the range of measured values, the time variability of the parameter of interest and the availability of resources. In the absence of sufficient background information, an arbitrary frequency based on knowledge of local conditions is chosen. After sufficient data have been collected, the frequency may be adjusted to reflect the observed variability. The frequency is also influenced by the relative importance of the station and whether or not the concentrations approach critical levels for some substances measured.

For lake stations, the recommended practice is to sample five consecutive days during the warmest part of the year and five consecutive days every quarter. Special cases include temperate-zone lakes that experience stratification. These should be sampled at least six times a year, together with the occasional random sample, to cover the following periods: during open water prior to summer stratification, during mixing following summer stratification, under ice, and during the periods of snow melt and runoff. Similarly, additional samples of rivers should be taken, if possible, after storm events and during snow melt and runoff.

When parameters are plotted against time, some cyclic variation may be apparent amidst the random fluctuations. The detection of cyclic events requires a sampling interval no longer than one third of the shortest cycle time and sampling over a period at least ten times longer than the time of the longest cycle. Therefore, long-period cycles will not be verified in the initial surveys, but become apparent during the operation of the network. In order to detect the cyclic variations, some random sampling is desirable, for example, on different days of the week or different hours of the day.

2.4.3.3 Precipitation quality

In general, sampling sites should be selected to give accurate and representative information concerning the temporal and spatial variation of chemical constituents of interest. Important factors to take into consideration are prevalent wind trajectories, sources for compounds of interest, frequency of precipitation events (rain, snow, hail), and other meteorological processes that influence the deposition. There are also local criteria to be considered:

(a) No moving sources of pollution, such as routine air, ground, or water traffic, should be within 1 000 m of the site;
(b) No surface storage of agricultural products, fuels, or other foreign materials should be within 1 000 m of the site;
(c) Samplers should be installed over flat undisturbed land, preferably grass-covered, surrounded by trees at distances greater than 5 m from the sampler. There should be no wind-activated sources of pollution nearby, such as cultivated fields or unpaved roads. Zones of strong vertical eddy currents, eddy zones leeward of a ridge, tops of wind-swept ridges and roofs of buildings, particularly, should be avoided because of strong turbulence;
(d) No object taller than the sampler should be within 5 m of the site;
(e) No object should be closer to the sampler than a distance of 2.5 times the height by which the object extends above the sampler. Particular attention must be given to overhead wires;
(f) The collector intake should be located at least 1 m above the height of existing ground cover to minimize coarse materials or splashes from being blown into it;
(g) Automatic samplers require power to operate lids and sensors, and in some cases for refrigeration in the summer and thawing in the winter. If power lines are used, they must not be overhead. If generators are used, the exhaust must be located well away and downwind from the collector;
(h) To address issues on a continental scale, sites should preferably be rural and remote, with no continuous sources of pollution within 50 km in the direction of the prevalent wind direction and 30 km in all other directions.

It may not be possible to meet all of these criteria in all cases. The station description should refer to these criteria and indicate the exact characteristics of each location chosen as a sampling site.

In the case of large lakes, the precipitation over the lake may not be as heavy as along the shores and the proportion of large particles may be smaller. In order to sample in the middle of a lake, the sampler can be mounted on a buoy, rock, shoal or small island.

Event sampling is the preferred method for sampling precipitation. Each rain shower, storm or snowfall constitutes an event. The analysis of event-precipitation samples enables pollutants associated with a particular storm to be determined, and a wind-trajectory analysis can determine probable sources. However, this sampling regime is very sensitive. The same statistical considerations concerning frequency of sampling apply here as for surface-water sampling.

2.4.3.4 Sediment quality

Most of the selection criteria outlined in previous sections also apply to sampling for sediment. Therefore only additional special recommendations will be described here.

For rivers where sediment-transport data are required, it is necessary to locate the sampling sites near a water quantity gauging station so that accurate stream discharge information is available at all times. Sampling locations immediately upstream from confluences should be avoided because they may be subjected to backwater phenomena. In streams too deep to wade, locate sampling sites under bridges or cableways. When sampling from bridges, the upstream side is normally preferred. Sampling in areas of high turbulence, such as near piers, is often unrepresentative. Attention also must be paid to the accumulation of debris or trash on the piers, as this can seriously distort the flow and hence the sediment distribution. An integrated sample obtained by mixing water from several points in the water column according to their average sediment load can be considered as a representative sample as long as there is good lateral mixing.

The best places to sample bottom deposits in fast-flowing rivers are in shoals, at channel bends and at mid-channel bars or other sheltered areas where the water velocity is at its minimum.

Sampling sites should be accessible during floods, since sediment-transport rates are high during these times.

For identification of peak pollution loads in rivers, two cases must be considered:

(a) For pollution from point sources, sampling should be done during low-flow periods, when pollution inputs are less diluted;
(b) When pollutants originate from diffuse sources such as runoff from the land of agricultural nutrients or pesticides, sampling must be focused on flood periods during which the pollutant is washed out of the soil.

If one of the objectives is to quantify the transport of sediment in the river system, it should be noted that peak concentrations of sediment do not necessarily correspond with times of peak flow. Also, a series of high flow rates will lead to progressively lower sediment peaks – an exhaustion effect arising from the depletion of material available for re-suspension.

For lakes, the basic sampling site should be located at the geographic centre of the lake. If the lake is very large (area > 500 km^2), several base stations may be needed. If various sediment types must be sampled, then data from acoustic surveys (echo-sounders) can be used both to identify the type of surficial material (sand, gravel or mud) and to indicate the presence of layering below the surface. Secondary sampling sites should be located between the base station and major tributary inlets or pollutant sources. A common strategy is to place points down the long axis of the lake with occasional cross-lines. Three to five stations should usually give a good approximation to the sediment quality of an average size lake. For statistical validity, however, a larger number of sampling sites will probably be required.

Sampling frequency in lakes is affected by the generally low concentrations of suspended sediment. Sediment traps should be operated during periods of maximum and minimum algal productivity and at times of high input of sediment from rivers.

Repeat sampling of bottom sediments in lakes needs to take into account the rates of sediment accumulation. Basins in cool temperate climates often have accumulation rates in the order of 0.1–0.2 mm per year. A resampling period of five years would then be too soon to provide worthwhile new information, unless the presence of a new pollutant is to be tested.

2.4.3.5 Groundwater quality

A great deal of hydrogeological information may be necessary to plan the sampling strategy for aquifers. Water levels, hydraulic gradients, velocity and direction of water movements should be known.

An inventory of wells, boreholes and springs fed by the aquifer should be drawn up, and details of land use should be recorded.

Groundwater samples are taken from drainage water, open wells and drilled wells. Wells should be sampled only after they have been pumped long enough to ensure that a fresh sample has been obtained. This is particularly necessary where a well has a lining subject to corrosion.

An existing well is a low-cost choice, although wells are not always at the best location or made of non-contaminating materials. A well that is still in use and pumped occasionally is preferable to one that has been abandoned. Abandoned or unused wells are often in poor condition with damaged or leaky casings and corroded pumping equipment. It is often difficult to measure their water levels, and they may be safety hazards.

Changes in groundwater quality can be very slow and are often adequately described by monthly, seasonal or even annual sampling schedules.

2.4.4 Operational data acquisition networks

Many types of hydrological forecasts are compiled on the basis of data from networks. Information may include measurements, as well as details of the operation of water-management and flood-protection works. A forecast system should make use of data from the basic network (2.4.1.3) as far as possible. The scope of the forecast network is determined by:

(a) User demands for forecasts at specified locations and for current information on the status of water bodies;
(b) The network density needed to describe the hydrological characteristics and the dimensions of water bodies;
(c) The technology for data transmission to the forecast centre;
(d) The representativeness of the observations;
(e) The media for issuing forecasts.

The information on water-management operations should be organized to fit in with the normal operational routines of the water-management agencies that supply the information.

A schedule of reports transmitted to the forecast centre by non-automatic monitoring stations should be drawn up, and the reports should be classified according to whether they are regularly or occasionally transmitted. The regular reports should include daily information on water levels, discharge and temperature and, where appropriate, ice phenomena, as well as observations every 5 or 10 days on ice thickness, snow depth and water equivalent. The occasional reports contain emergency information on significant changes in the regime of water bodies and operational control strategies, as well as specially requested reports that are needed to define the development of particular hydrological phenomena.

The *Casebook on Hydrological Network Design Practice* (WMO-No. 324) gives examples of spatial densities for various hydrological variables and the general principles for determining them based on the time and space variability.

2.4.5 Network-strategy options

In addition to seeking to improve representativeness of existing surface-water data networks, Hydrological Services should develop more comprehensive monitoring strategies. For selected basins, the hydrometric data-collection activities need to be integrated with sediment, water quality, meteorology and aquatic-habitat programmes (2.4.1.4). For example, concerns for sediment-associated contaminant transport require knowledge of the source, pathways and fate of fine particles. This requires an understanding of both the flow and sediment regimes. Whether for the interpretation of concentrations or for calculating contaminant loadings, such integrated monitoring requires close coordination at all stages from planning to reporting.

Integrated planning of related data networks should be developed to maximize the effectiveness of all water-data programmes. Significant efforts are required to define network needs from many different perspectives, and, ultimately, to coordinate the data collected on a watershed basis so that adequate water data, that is, precipitation, runoff, groundwater and water quality, are available to meet future needs.

Present monitoring programmes can be enhanced by the use of supplementary studies. For example, river studies of sediment sources and morphologic change (Church and others, 1989; Carson, 1987) supplement regular programme data to determine the river behaviour. This knowledge, which is not acquired from monitoring studies alone, is being used for fisheries management, river-engineering studies and water-quality studies.

On a different scale, water-quality considerations are increasingly important to urban drainage design.

The design of appropriate monitoring programmes should consider short-interval sampling, integrated precipitation and runoff monitoring, and extremely rapid response times if the data are to be useful. These conditions are quite different from those covered by standard monitoring procedures. The use of computer models is an additional strategy for enhancing the information derived from water-monitoring activities. In certain circumstances, monitoring-network designs can be improved by the use of models.

2.5 DATA COLLECTION

2.5.1 Site selection

Once the network design phase has been completed, the operational requirements have established the general location of the data-collection sites, and the types of instrumentation have been identified, the best specific site in the general location is selected to meet the requirements of the instrumentation as outlined in subsequent chapters of this Volume (5.3.2.1 and 5.4.2). Modifications to the site may be necessary to ensure the quality of the data, for example, clearing and control stabilization.

When a site has been selected and the instrumentation has been installed, two types of data will be collected at the site: descriptive details of the site and its location, and the hydrological observations that it has been established to measure. Once established, the installation should be operated and maintained to its predetermined standard. In general, this involves the execution of an adequate schedule of inspection and maintenance to ensure continuity and reliability of data, and the development of routine check measurements and calibrations to ensure data of the required accuracy.

2.5.2 Station identification

Two aspects should be considered to ensure the historical documentation of details of a data-collection site: the institution of an identification system and the archival of descriptive information.

2.5.2.1 Identification of data-collection sites

Every permanent site should be given a unique identifier that will be used to denote all data and other information pertinent to the site. Such identifiers are usually numeric, but they may also be alphanumeric.

Frequently, more than one service or agency may be operating data-collection sites in one particular region or country. The acceptance by all parties of a single, unique system of site identification will facilitate data interchange and the multiparty coordination of data-collection activities. The region chosen should be determined by drainage basin(s) or climatic zones, and part of a site's identification should reflect its location in the region.

The site identification can be simply an accession number, that is, a sequential number assigned as stations are established. For example, site identification in the Canadian National Water Quality Data Bank, NAQUADAT, represents a sophisticated system designed for computer processing. It has a 12-digit alphanumeric code, which is the key element in storing and retrieving data in the computer system. This number is composed of several subfields (UNEP/WHO, 1996), as follows:

(a) Type of water – a two-digit numerical code indicating the type of water sampled at any given location, such as streams, rivers and lakes, or precipitation. The meaning of this code has been extended to include other types of aquatic media. A list of all currently assigned codes is given in Table I.2.8;
(b) Province, basin and sub-basin – three pairs of digits and letters identifying the province, basin and sub-basin;
(c) Sequential – a four-digit number assigned usually by a regional office.

For example, station number 00BC08NA0001 indicates that the sampling site is on a stream, in the province of British Columbia, in basin 08 and in sub-basin NA, and the sequence number is 1. Station number 01ON02IE0009 is on a lake, in the province of Ontario, in basin 02 and in sub-basin IE and the sequence number is 9.

WMO has accepted a coding system for station identification (Moss and Tasker, 1991) that is similar to (b) and (c) of the NAQUADAT system.

Another well-known coding system for sampling points is the River Mile Index used by the Environmental Protection Agency of the United States as part of the STORET system. In this system, the location of a sampling point is defined by its distance and hydrological relationship to the mouth of a river system. It includes major and minor basin codes, terminal stream numbers, the direction and level of streamflow, the mileages between and to confluences in the river system, and a code to identify the stream level on which the point is located.

Table I.2.8. NAQUADAT codes for types of aquatic media

Type	*Code*	*Subtype*	*Code*
Surface water	0	Stream-channel	0
		Lake	1
		Estuary	2
		Ocean-sea	3
		Pond	4
		Impounded reservoir	5
		Harbour	6
		Ditch	7
		Runoff	8
		Unknown	9
Groundwater	1	Well-sump	0
		Spring	1
		Piezometer well	2
		Tile drain	3
		Bog	4
		Household tap	8
		Unknown	9
Waste-treated	2	Industrial	0
		Municipal	1
		Mining	2
		Livestock waste	3
		Unknown	9
Precipitation	3	Rain	0
		Snow	1
		Ice (precipitated)	2
		Mixed precipitation	3
		Dry fallout	4
Treated supply	4	Municipal	0
		Industrial	1
		Mining	2
		Private (individual)	3
		Other communal works	4
		Municipal distribution	5
		Municipal treatment plant (intermediate)	6
		Treatment residue or sludge	7
		Other	9
Sediments, soils	5	Stream channel	0
		Lake bottom	1
		Stream bank	2
		Lake bank	3
		Contaminated by soil	4
		General soil	5
		Effluent irrigation soil	6
		Sludge or conditioned soil	7
		Other	8
Industrial waste water	6	Storm water	0
		Primary influent	1
		Primary effluent	2
		Final effluent	3
		Sludge	4
		Special problem	5
		Other	6
Municipal waste water	7	Raw	0
		Primary lagoon effluent	1
		Secondary lagoon effluent	2
		Conventional primary effluent	3
		Conventional secondary effluent	4
		Advanced waste water treatment effluent	5
		Disinfected effluent	6
		Raw sludge	7
		Digested sludge	8
		Other	9
Miscellaneous waste water	8	Raw	0
		Primary lagoon effluent	1
		Secondary lagoon effluent	2
		Conventional primary effluent	3
		Conventional secondary effluent	4
		Advanced waste water treatment effluent	5
		Disinfected effluent	6
		Raw sludge	7
		Digested sludge	8
		Other	9

Source: World Meteorological Organization, 1988*a*: *Manual on Water Quality Monitoring – Planning and Implementation of Sampling and Field Testing*. Operational Hydrology Report No. 27, WMO-No. 680, Geneva.

2.5.2.2 Descriptive information

In many instances the value of the data will be enhanced if the user can relate it to the details of the history of its collection as part of the routine production of metadata. To this end, a station registration file should record the details of each station. The level of detail will of course vary with the parameter monitored. Typical information would include the station name and location details, the station type, the associated stations, establishing/operating/owner authorities, the elevation details, the frequency of observation, the operating periods and the details of installed equipment. Additional items specific to the station type should also be included. Selected information from this text file should be attached routinely to any data output (Chapter 10).

A historical operations file of more detailed information should also be prepared for release as required (Chapter 10). Again, the level of detail will vary with the type of observations being recorded. A stream station may include details such as climate zone and rainfall and evaporation notes, geomorphology, landforms, vegetation, land use and clearing, and station details. Typical components of such a file would include the station description, a detailed sketch of the site, a map showing the location of the site in the region, and a narrative description of the site and region. Some examples of the format of such files can be found in the UNEP (2005) and Environment Canada (1983) publications. Figure I.2.10 is an example of one format.

2.5.2.2.1 *Station description*

An accurate description of the sampling location includes distances to specific reference points. It is important that these reference points be permanent and clearly identified. For example, "5 metres north-west of the willow sapling" is a poor designation for a data site. An example of a useful description is "30 metres downstream from Lady Aberdeen Bridge (Highway 148), between Hull and Pointe Gatineau and 15 metres off the pier on the left side looking downstream". If hand-held global positioning devices are available, the geographic coordinates of the sampling location should be determined and recorded on the station description. The dates that the station was first established and that data collection was commenced should also be recorded.

For streamflow and water-quality data stations, location information should also include descriptions of the water body above and below the station. These should include water depths, a description of the banks on either side of the water body and the bed material. A description of the water body should include any irregularities in morphology that might affect the flow of water or its quality. Such irregularities may include a bend in a river, a widening or narrowing of the channel, the presence of an island, rapids or falls, or the entry of a tributary near the station. A description of the banks should mention slope, bank material and extent of vegetation. Bed or sediment material may be described as rocky, muddy, sandy, vegetation-covered, etc. Station-location descriptions

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STATION LOCATION DESCRIPTION

REGION Quebec

PROVINCE Quebec BASIN Ottawa River

STATION DATA

TYPE	PROV.	BASIN	SUB-BASIN	SEQUENT	
0 0	QU	0 2	L H	0 0 3 6	0 0 0

LATITUDE S	DEG	MIN	SEC	LONGITUDE S	DEG	MIN	SEC	PR
	4 5	2 7	2 5 0 0		0 7 5	4 2	0 2 0 0	5

UTM ZONE	S	EASTING	S	NORTHING	PR
		0			

STATION LOCATION

Reservoir / Stream / Lake / River

On Gatineau

At Lady Aberdeen bridge near Pte. Gatineau Prov. Que.

Located in ____ Sec. ____ Tp ____ Region ____

Established April 19 78

Distance from base to station 1.5 km

Distance from station to site of analysis 17 km

Location of station with respect to towns, bridges, highways, railroads, tributaries, islands, falls, dams, etc.:

30 m downstream of Lady Aberdeen bridge (Highway 148) between Hull and Pointe Gatineau and 15 m off pier on left side (looking downstream)

Description and location of nearby hydrometric installations:

Baskatong dam about 190 km upstream
Farmers rapids about 25 km upstream

STATION DESCRIPTION

Direction of flow:
South-east

Description of channel above station:
Permanent log boom on right, gradual curve to left

Description of channel below station:
Gradual widening before emptying into Ottawa r.; main current on left, slight backwater on right

Description of left bank:
Approx. 3 m drop to river; slope allows only shrubby vegetation

Description of right bank:
Edge of park land; gentle slope

Bed: rocky, gravel, sandy, clean, vegetated:
Probably wood chips, muddy

Approximate dimensions and descriptions of lakes and/or reservoirs:
None

OBSERVATIONS

Natural conditions and/or control installations which may affect flow regimes:
Baskatong dam
Farmers rapids

Sources of chemical or physical inputs:
Logs, local sewage input

Figure I.2.10. Station-location forms

should mention seasonal changes that may hinder year-round data collection. Additional information in the case of lakes could include surface area, maximum depth, mean depth, volume and water residence time.

Additional information about conditions, either natural or man-made, which may have a bearing on the data should be recorded. Past and anticipated land disturbances and pollution sources should be mentioned, for example, forest fires, road construction, old mine workings, and existing and anticipated land use.

2.5.2.2.2 *Detailed sketch of station location*

A sketch of the location and layout of the station (including distances expressed in suitable units) with respect to local landmarks and permanent reference points, such as benchmarks, should be prepared (Figure I.2.11). Sampling or measuring sites and equipment locations should be prominently shown on the sketch.

2.5.2.2.3 *Map*

A large-scale map (Figure I.2.12) that locates the site with respect to roads, highways and towns should be included. The combination of the map and the sketch of the station location should provide complete location information. An investigator travelling to the site for the first time should have enough information to locate the station confidently and accurately.

2.5.2.2.4 *Coordinates*

Geographical coordinates are recorded as latitude and longitude and, in addition, coordinates may be recorded in other reference systems such as universal transverse mercator (UTM) coordinates or legal land descriptions. If the site is on a stream, its distance upstream from a reference point, such as a reference station or a river mouth should be recorded. National grid references, if available, should also be provided. For the international GLOWDAT (that is, GEMS/WATER data bank (UNEP, 2005) station), one entry is the WMO code for the octant of the globe for the northern hemisphere: 0, 1, 2 and 3 for 0–90°W, 90–180°W, 180–90°E and 90–0°E, respectively (WMO-No. 683). Correspondingly, for the southern hemisphere the codes are: 5, 6, 7 and 8 for 0–90°W, 90–180°W, 180–90°E and 90–0°E (WMO-No. 559).

Latitude and longitude values should be obtained using a global positioning system or, if that is not possible, from 1:50 000 or 1:250 000 topographical maps. Points on a 1:250 000 map can be located to about ±200 m and on a 1:50 000 scale to about ±40 m (WMO-No. 559). If available, navigational charts can be used to provide more accurate values than the topographical maps.

2.5.2.2.5 *Narrative description*

For streamflow and water-quality sites, it is recommended that the narrative description begin with the name of the river, stream, lake, or reservoir, followed by its location (for example, upstream or downstream) and its distance (to 0.1 km or better) from the nearest town, city, important bridges, highways or other fixed landmarks. The name of the province, territory or other geopolitical division should also be included.

Information concerning changes at the site, including instrumentation changes, should be added to the narrative description to provide a historical description of the site and the region that

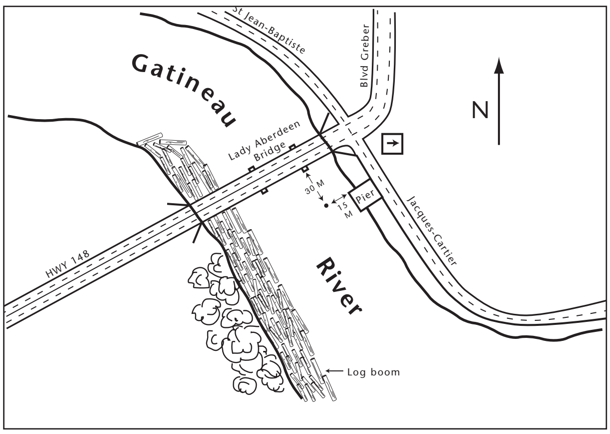


Figure I.2.11. Sketch of station layout

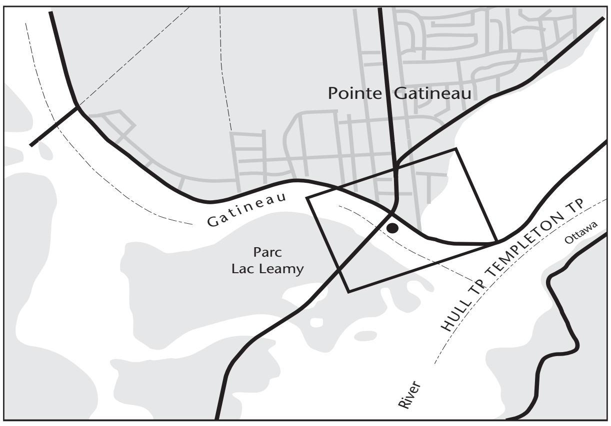


Figure I.2.12. Station-location map

it represents. Chapter 10 contains a suggested format for such information.

2.5.3 Frequency and timing of station visits

The frequency and timing of readings and thus visits to the site should be determined by the anticipated data usage and should be adequate to define the observations over time. Station visits will thus be for purposes of observation or collection of data and for maintenance of the site.

When the variable of interest at the site is changing rapidly, visits to manual stations must be more frequent if a valid record is to be maintained. Under such conditions, it may be more efficient to install automatic recording equipment or real-time transmission if funds and trained staff are available. This applies particularly where more frequent observations are desirable for hydrological purposes during storms and flood periods, as well as in tidal reaches of rivers.

2.5.3.1 Manual stations

There is considerable merit in encouraging the taking of observations at climatological stations at specified synoptic hours. WMO recommends (WMO-No. 544) that the time at which three-hourly and six-hourly weather observations are taken at synoptic stations are 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 universal time coordinated (UTC). In most countries, such stations are the key stations of the meteorological and climatological observation programmes. If the observer is to take three observations per day, the synoptic hours most conveniently related to normal times of rising and retiring and that nearest noon should be specified. For stations at which only one or two observations per day are taken, it should be possible to select synoptic hours for the observations.

It is recommended that all observers making only one observation per day should have a common observation time, preferably in the morning.

Some streams, for example small mountain-fed streams, may experience diurnal fluctuations in water levels during some seasons. Stage observations should initially be made several times a day at new stations to ensure that a single reading is an adequate representation of daily water level. Also, small streams may exhibit “flashy” behaviour in response to rain storms. Additional stage readings should be obtained during these times to adequately define the hydrograph. Stage observations should also be made at the time of water-quality sampling.

While it is desirable to have regular observations at synoptic hours, in some cases this will not be possible. In these cases, it is important that observations be taken at the same time each day and that this time be recorded in UTC or local standard time using 24-hour clock designations. If “summer time” (daylight saving time) is introduced for part of the year, arrangements should be made to have observations taken at the same hour, by UTC, as in the period prior to and following “summer time”.

The designated time of climatological observations should be the end of the time at which the set of observations is taken at a station. The set of observations should be taken, if possible, within the 10-minute period prior to the stated observational time. However, it is important that the actual time of observation be recorded carefully, whether the observation is taken at a standard time or not. In tidal reaches of rivers, the times of observation should be related to the tidal cycle.

2.5.3.2 Recording stations

The frequency and timing of visits to recording stations will be constrained by the length of time that the station can be expected to function without maintenance. For example, some continuous rainfall recorders record on a weekly strip chart and, thus, require weekly visits to remove and replace charts. Other instruments have much larger data storage capabilities and, therefore, require less frequent visits. A balance must be achieved between the frequency of the visits and the resultant quality of the data collected. Too long a time between visits may result in frequent recorder malfunction and, thus, in loss of data, while frequent visits are both time consuming and costly. Various studies have been carried out on the cost-effectiveness and efficiency of data collection. Further details are found in the *Proceedings of the Technical Conference on the Economic and Social Benefits of Meteorological and Hydrological Services* (WMO-No. 733).

The frequency of the visits may also be determined by accuracy requirements of the data. Some data-collection devices may suffer a drift in the relationship between the variable that is recorded and that which the recorded value represents. An example of this is a non-stable stage-discharge relationship. In such cases, visits to the station are required periodically in order to recalibrate the equipment or the measurement equations.

2.5.3.3 New technologies

The introduction of data loggers and telephone/satellite data transmission may have a significant impact on station inspection/data-collection frequencies (2.5.6). However, it should be noted that in order to ensure the quality of the data, regular station maintenance is necessary.

2.5.4 Maintenance of sites

The following maintenance activities should be conducted at data-collection sites at intervals determined to ensure that the quality of the data being recorded is adequate. These activities could be conducted by the observer responsible for the sites, if there is one. However, they should occasionally be performed by an inspector (9.8.4).

All collection sites:
(a) Service the instruments;
(b) Replace or upgrade instruments, as required;
(c) Retrieve or record observations;
(d) Perform the recommended checks on retrieved records;
(e) Carry out general checks of all equipment, for example, transmission lines;
(f) Check and maintain the site to the recommended specifications;
(g) Check and maintain access to the station;
(h) Record, in note form, all of the above activities;
(i) Comment on changes in land use or vegetation;
(j) Clear debris and overgrowth from all parts of the installation.

Streamflow collection sites:
(a) Check the bank stability, as necessary;
(b) Check the level and condition of gauge boards, as necessary;
(c) Check and service the flow-measuring devices (cableways, etc.), as necessary;
(d) Check and repair control structures, as necessary;
(e) Regularly survey cross-sections and take photographs of major station changes after events or with vegetation or land-use changes;
(f) Record, in note form, all of the above activities and their results;
(g) Inspect the area around or upstream of the site, and record any significant land-use or other changes in related hydrological characteristics, such as ice.

Further details are found in the *Manual on Stream Gauging* (WMO-No. 519).

Flood gauging cannot be programmed as part of a routine inspection trip because of the unpredictable nature of floods. A flood action plan should be established prior to the beginning of the storm season and should include priority sites and types of data required. If flood gaugings are required at a site, the preparations must be made during the preceding dry season so that all is ready during the annual flood season. Additional measures may be required if severe flooding is likely.

Preparations include:
(a) Upgrade site access (helipad, if necessary);
(b) Equip a temporary campsite with provisions;
(c) Store and check gauging equipment;
(d) Flood-proof instrumentation such as stage recorders.

Following the recession of flood waters, particular attention is required to ensure the safety and security of the data-collection site and to restore normal operation of on-site instrumentation. In some cases redesign and reconstruction of the site will be required. This work should take into account information obtained as a result of the flood.

2.5.5 Observations

At all data-collection sites a value must first be sensed, then encoded or recorded, and finally transmitted. Examples of the components of data collection are displayed in Table I.2.9.

2.5.5.1 Manual stations

At the very minimum, observers should be equipped with field notebooks and/or station journals in which the original observations are recorded as they are taken. Forms should also be provided to permit the observer to report observations daily, weekly, fortnightly, or monthly, as required. The field notebook or station journal should be retained by the observer in case the report is lost in transit.

The report forms should be designed to permit easy copying of the results from the field notebook or station journal. A good approach is to have the report form identical to a page in the notebook or journal. At least, the various elements should be in the same columns or rows in both. Space should be allowed in the journal and, perhaps, in the report form for any conversions or corrections that may have to be applied to the original readings.

Alternatively, an observation notebook with carbon paper between successive sheets will permit easy preparation of an original form for dispatch to the central office and a copy for the local station record. This is not a satisfactory procedure where the notebook is to be carried into the field as moisture can easily make the entries illegible. The report forms may also be coding forms suitable for direct conversion to computer medium.

The value of data can be greatly enhanced – or devalued – by the standard of the accompanying documentation. Observers should be encouraged to comment on any external influences that may affect observations, whether they be related to equipment, exposure, or short-term influence. In addition, input formats and forms should be flexible enough both to allow comments to be appended and for these comments to be accessible with the final data. It is important that published comments be expressed in standard terminology, and it is preferable that correct vocabulary be employed in the field report.

There is also reason for setting up the processing system so that quality coding or tagging is carried out as the observations are made. This is particularly applicable to manual observations because it encourages the making of judgements while the conditions are being observed. Data from field measurement books may be processed using optical readers or portable field computers that will allow the direct input of observations into computer storage. Such devices allow for reduced data transfer errors and automatic data quality checks.

Field observations that may assist in interpreting water quality should be entered on the report. These observations may include unusual colour or odour of the water, excessive algal growth, oil slicks, surface films, or heavy fish kills. Such observations may prompt the field investigator to take additional observation-based samples, in addition to those required by the routine schedule. The types of samples and their preservation should be consistent with the types of analysis that the investigator thinks is warranted by the prevailing conditions. If additional samples are collected at sites other than the established station, the description of their locations should be recorded accurately. This kind of information and the additional samples may prove very useful in the interpretive phase of the study.

Table I.2.9. The components of data collection

Data collection		
Data capture		*Transmission*
Sensing	*Recording*	
1. Visual Water-level gauge, land use, site description, soil texture, etc.	1. Field notebook Text descriptions and element or parameter values	1. Manual Field observers Postal services Telephone
2. Mechanical Raingauge, thermometer, current meter, soil penetrometer, water level gauge	2. Field data sheet Purpose designed for particular text decriptions and element or parameter values May be pre-coded for subsequent computer input purposes	2. Automatic (Telemetry) Telephone Dedicated landline Radio Satellite Internet Mobile phone networks
3. Electrical Thermistor, radiometer, pressure transducer, conductivity probe, encoder	3. Charts Strip charts with element value continuously recorded by pen tracing	
	4. Computer compatible media (a) Manually recorded Mark sense forms Multiple choice forms (b) Automatically recorded Solid state memory	

Note: The table applies to elements or parameters observed in the field. There are notable groups of data, for example, in soils and water quality, where laboratory analysis or physical samples are performed. Here the data-collection system almost invariably is:
(a) Mechanical sampling
(b) Notebook/data sheet field entries.

2.5.5.2 Recording stations

At automatic recording stations, observations are recorded in digital or graphical form. However, the following observations should be recorded at the time of any visits for data retrieval or station maintenance:

(a) Site identification number;
(b) Observations from independent sources at the time of collection, for example, gauge boards and storage rainfall gauges;
(c) Specific comments relating to the recording device, including its status, current observation and time.

Each inspection should be recorded by completing a station-inspection sheet. Data may be recorded in solid-state memory or perforated tape. Final extraction of observations from the recorded data may be performed at computing facilities when removable memory of perforated tape has been used as the recording medium. However, portable computers may be used to extract data directly from data loggers and to verify the data before leaving the station. Field verification allows any necessary repairs or other changes to be made before leaving the site.

Data loggers record data at specific time intervals (as programmed by the user). Intelligent loggers will also allow for data compaction and variability of observation times. In the case of the observation of multiparameters, the coordination of observations can also be performed by the intelligent field logger. For example, rainfall data can be recorded at a five-minute interval or at every tip of a bucket, for stage data when the level alters by more than 1 cm, and water-quality parameters when stream height alters by 10 cm and/or on a 24-hour basis.

With graphical recorders, observations are collected continuously and processing of the data in the office is required. Comments should be written on the chart or noted on the inspection sheet if any errors are detected. As with digital recorders, independent field observations should be made and recorded during each site visit.

After a station has been in operation for a reasonable period, the frequency and timing of inspections should be re-assessed in the light of the capabilities of the instrumentation and the requirements for data at that site. In some cases, consideration should be given to the real-time collection of data via various communications options as a cheaper method of data collection than regular site visits (2.5.6).

2.5.5.3 Real-time reporting

There are many recording and non-recording stations from which real-time data are required, for example, in the operation of reservoirs, flood-warning and forecasting situations, and in some instances as a cost-effective method of data collection.

Real-time data collected by field observers must be reported using a transmission facility, such as a radio or the public telephone system, to the agency. Similarly, recording stations must report via some transmission facility. Recording devices may have the advantage of being able both to transmit data at prescribed intervals/parameter changes and be interrogated by the collecting agency to determine the current situation or reset observation intervals. Data loggers may also provide information on the current available storage capacity of the logger and the condition of the available power supply. Automated quality-control processes can be developed in these situations.

2.5.5.4 Instructions for observers

Clearly written instructions must be provided to all observers. These should contain guidance and directions on the following matters:

(a) A brief description of instruments, with diagrams;
(b) Routine care and maintenance of instruments and actions to be taken in the event of serious breakage or malfunctioning;
(c) Procedures for taking observations;
(d) Times of routine observations;
(e) Criteria for the beginning, ending and frequency of special non-routine observations, for example, river-stage observations while water level is above a predetermined height;
(f) Procedures for making time checks and putting check observations on charts at stations with recording instruments;
(g) Completion of field notebooks or station journals;
(h) Completion of report forms, including methods of calculating means and totals with appropriate examples;
(i) Sending of reports to the central office;
(j) Special routines for real-time stations.

Such written instructions should be supplemented by oral instructions by the inspector to the observer at the time of installation of instruments and at regular intervals thereafter.

The instructions should emphasize the importance of regular observations with perhaps a brief account of how the observed data are used in water resources development, hydrological forecasting, or flood-control studies. Any special observations that may be required during special periods, for example, during floods, or any special reports that are to be filed, should be specifically discussed. Observers should be urged not to forget to fill in the spaces for station names, dates and their signature. The necessity of reporting immediately any instrument failure or significant modification of the observing site should be emphasized.

Observers at stations equipped with automatic recording instruments must be provided with instructions on the method of verifying the operation of digital recorders, changing charts and taking check observations. These instructions must stress the importance of annotating the chart with all information that might be required for later processing. This would include station identification, time on, time off, check-gauge readings and any other entries that would make the record more easily interpreted at a later time.

At stations with full-time personnel, the staff should be sufficiently well trained to abstract data from recording instruments. For such stations, carefully worded instructions on the method of abstracting data and on the completion of report forms must be provided. However, at many ordinary stations, where observers may not be thoroughly trained, it may be undesirable to require observers to undertake the relatively complex job of data abstraction. In such cases, digital or graphical records should be forwarded to a central office for processing of the data.

2.5.6 Transmission systems

2.5.6.1 General

During recent years, the demands from users of hydrological data have become more and more complex; therefore, systems that include automatic transmission of hydrological observations have been incorporated into national networks. This has also led to the need for developing codes to facilitate the formatting of observations for the transmission and dissemination of forecasts. Hydrological codes are discussed in 2.3.2. The following describes different possibilities for transmission systems:

(a) Manual – The observer at the station mails data or initiates radio or telephone calls to the central office on pre-arranged criteria;
(b) Manual/semi-automatic – The central office manually interrogates the remote automatic station by telephone, Internet, radio or radio telephone or satellite, and receives single discrete values as often as interrogated. It is possible to have automatic telephone-dialing equipment in the central office that can make calls in series;
(c) Automatic timed – Automatic equipment at stations is programmed to initiate transmission of a single, instantaneous observation and/or past observations held in a storage register;
(d) Automatic event indicator – The station transmits automatically, by radio, telephone, Internet or satellite, a specified unit of change of a variable, for example, each centimetre change in the stage of a river;
(e) Automatic – Data are transmitted by the station and recorded at the central office on a continuous basis.

2.5.6.2 Transmission links

The possible choices of transmission links include:

(a) Dedicated land-lines – These are used where relatively short distances are involved and commercial lines are not readily available;
(b) Commercial telephone and telegraph lines – Telephone and telegraph systems can be used whenever feasible. Equipment that permits unattended reception of observations at the central office is available. Measurements and commands can be transmitted to and from the remote site;
(c) Commercial cellular telephone networks – The ever growing coverage of these networks, together with better and more reliable equipment, make them an interesting and less expensive option for moving data from a site and into the central office. The combination of reliability and low cost makes it more realistic to collect data from stations with no real-time interest, from sites previously considered as somewhat remote, to be transmitted using commercial facilities. Cellular systems can be used in the same way as standard telephone lines and may continue to operate during an extreme event when telephone lines fail;
(d) Direct radio links – These must be used when requirements cannot be met by those facilities provided by landlines, or when distances or natural obstacles prevent the economic installation of wires. Distances of several to hundreds of kilometres may be spanned by radio transmitters, depending upon the carrier frequency and the transmitter power. At the higher frequencies, the transmitter and receiver must have a clear line-of-sight transmission path. This limits the range without repeater

stations to about 50 km. In all cases, the installation and operation of radio transmission links are subject to national and international regulations;

(e) Satellite links – Data transmission using satellites can take place in two ways: transmission of data, as observed by sensors in the satellite (such as imagery) or the use of the satellite to relay data observed at remote ground stations to central receiving locations. At the present time, the science of observation and transmission or retransmission from satellites is developing rapidly. The data involved are available either directly from the spacecraft or through central data banks;

(f) The Internet – Internet Protocol communication in various forms, including the use of mobile phone networks, makes this an interesting and less expensive way to send data, especially if there is much data to transfer or continuous transfer is wanted. Internet communication works on a number of different physical communication paths, including both mobile and ordinary telephone networks. This makes it more reliable. In systems with a large number of sites, it also makes the retrieval time shorter and the communication system in the main office much easier.

2.5.6.3 Factors affecting the choice of transmission systems

When considering the possibility of including automatic transmission of data in any measuring system, consideration should be given to the following:

(a) Speed with which data are required. This depends upon the following factors:
   (i) The speed with which changes in the measured variable take place;
   (ii) The time between the observation and receipt of the data by conventional means, versus automatic transmission systems;
   (iii) The urgency of having this information available for warnings or forecasts;
   (iv) The benefits of forecasts from telemetered data and economic losses due to lack or delay of forecasts;
   (v) The advantages of radio and satellite transmission versus landlines in times of storms and floods when these disasters can destroy the more conventional means of telecommunications at the time that the information is most urgently needed;

(b) Accessibility of the measurement sites for quality control and maintenance;

(c) Reliability of the recording device. When local climatic conditions are rigorous, the operation of on-site mechanical equipment is difficult. Under these situations, it may be more reliable to transmit data electronically to a central climate-controlled office. This system also permits a continuous check of the operation of the sensors;

(d) Staffing for operational, maintenance and logistic problems. It is important for these aspects to be considered in the planning process and to recognize that each individual project will have its own particularities. Careful attention should be given to the costs and benefits of all the alternatives before any final decision is made. When designing a system for the automatic transmission of data, the main components to consider for staffing purposes are:
   (i) Sensors and encoding equipment;
   (ii) The transmission links;
   (iii) Receiving and decoding equipment.

It is necessary to consider these components jointly in the design stage. This is essential because the special characteristics of any one component can have serious consequences on decisions regarding the others. If the ultimate use of the data transmission system is intended for forecasting, then sensing, transmitting and receiving hydrometeorological data is an essential but insufficient component of the forecast system. A forecast centre having personnel who are well-trained in preparing forecasts and warnings, and in notifying persons at risk is also fundamental (United Nations, 2004).

2.5.7 Water-quality monitoring

Chapter 7 provides details of instrumentation and field practices for the collection of water-quality data. The sampling locations, the sampling times, the parameter identifications and the corresponding values must be recorded and coherence must be maintained throughout the handling of the data. If any one of these essential items is lacking, then the whole effort is wasted.

2.5.7.1 Station identification

The importance of an accurate written description of each station location and the conditions under which the samples are collected are discussed in detail in 2.5.2.2.

2.5.7.2 Field sheets for water-quality monitoring

Perhaps one of the most important steps in a sampling programme is the recording on the field sheets of observations, sampling date, time, location and the measurements made. All field records must be completed before leaving a station. Additional instructions are contained in 2.5.5.

Two examples of a systematic format for recording field analyses and observations are provided in Figures I.2.13 and I.2.14. The formats shown in these figures are appropriate for those personnel that use computer systems for storing their results. The format of Figure I.2.13 can be used by anyone collecting water-quality data. Both formats can be adapted to fit situations specific to a particular need. The following information is usually recorded:

(a) Sampling site and date;
(b) Field-measured parameters;
(c) Instrument calibration;
(d) Sampling apparatus used and procedures;
(e) Quality control measures used;
(f) General remarks and field observations.

2.5.7.3 Transportation of water-quality samples

Once collected, some water samples must be transported to the laboratory. The mode of transportation will depend on the geographic location and the maximum permissible time lapse before analysis for each constituent. The field investigator is responsible for delivering the samples to the airline, bus, train or postal terminal on schedule so that there will be minimal delay in sample transport. Logistics for sample transport and storage should be determined before fieldwork is initiated.

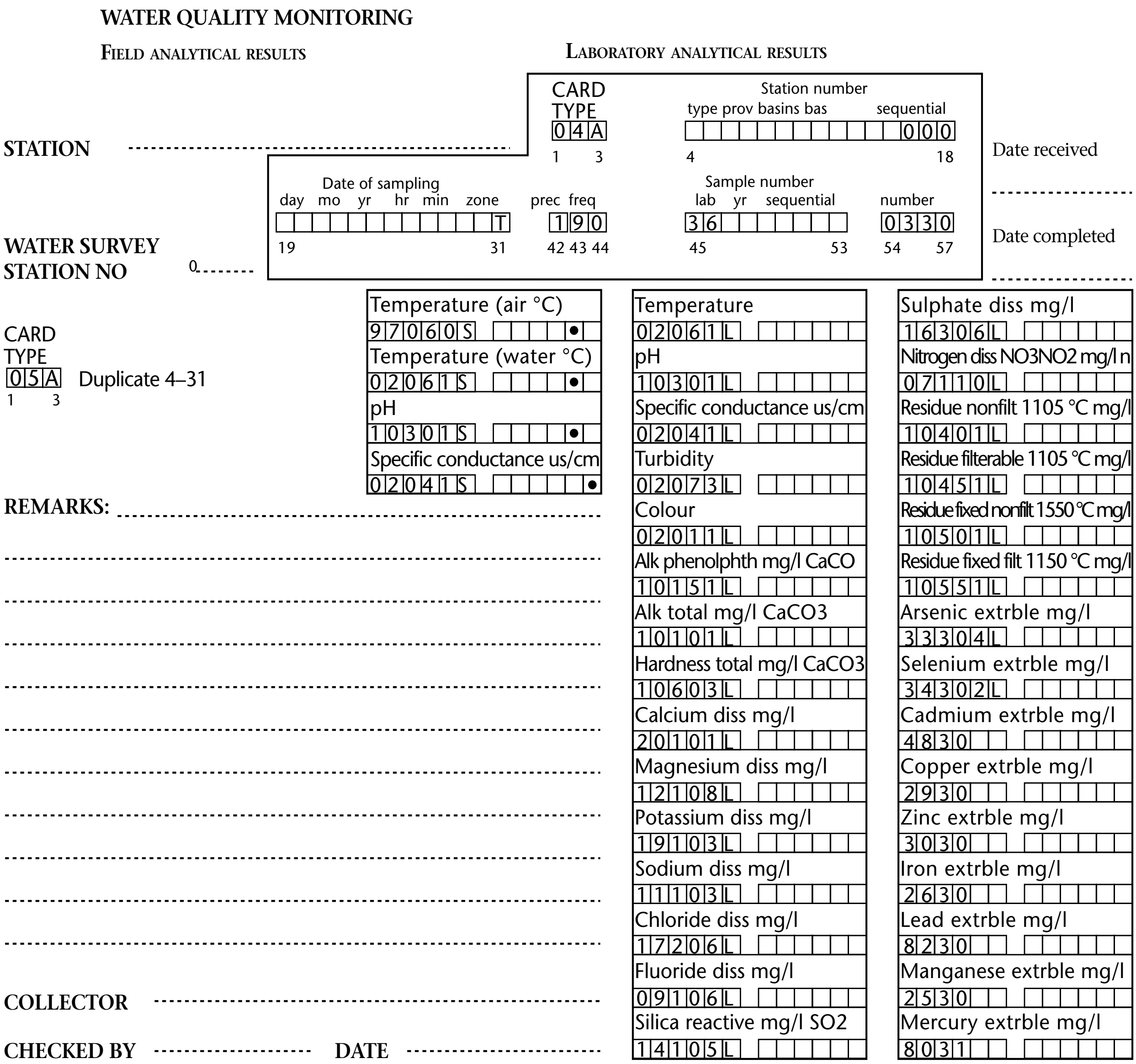


Figure I.2.13. Field sheet for use with NAQUADAT or similar computer system

STATION NO. ____________________
DESCRIPTION ____________________
____
DATE OF SAMPLING DY ____________ MO ____________ YR ____________
TIME OF SAMPLING HR ____________ MI ____________ TIME ZONE ____________
SAMPLED BY ____________________
FIELD MEASURED PARAMETERS
Water temp. °C ____________ Air temp. °C ____________
pH ________ Specific cond. ________ Diss. oxygen ________ Turb. ________
Depth of water ____________ Depth at which sample taken ____________
Ice thickness____________________
Other ____________________
Remarks ____________________
____
INSTRUMENT CALIBRATION
Diss. oxygen meter model ____________ Winkler calibration ____________ mg/L
Meter reading before adjustment ____________________
Conductivity meter model ____________________
pH meter model ____________ Calibration butters used ____________
Remarks ____________________
____
WATER QUANTITY MEASUREMENT DATA
Location description ____________________
____
Description of gauge ____________________
____
Stage height ____________________
Time ____________________

Figure I.2.14. General format for a field-sampling sheet

2.5.7.4 Field quality assurance in water-quality monitoring

A field quality assurance programme is a systematic process that, together with the laboratory and data-storage quality assurance programmes, ensures a specific degree of confidence in the data. A field quality assurance programme involves a series of steps. All equipment should be kept clean and in good working condition, with records kept of calibrations and preventive maintenance. Standardized and approved methodologies, such as those recommended in this Guide, should be used by field personnel.

The quality of data generated in a laboratory depends on the integrity of the samples that arrive at the laboratory. Consequently, the field investigator must take the necessary precautions to protect samples from contamination and deterioration. Further details on field quality assurance are available in Chapter 7 of the present Guide; ISO Standards (ISO 5667–14:1998 Water quality-Sampling – Part 14: Guidance on quality assurance of environmental water sampling and handling), in the *Water Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes* (UNEP/WHO, 1996); and the *Manual on Water Quality Monitoring: Planning and Implementation of Sampling and Field Testing* (WMO, 1988).

2.5.8 Special data collection

2.5.8.1 Requirement

Data concerning severe storms and floods are very important in determining design criteria for many types of hydraulic structures. In general, regular observation networks do not provide enough detailed information on storm-rainfall distribution, or on flood-peak discharges of tributary streams. In addition, during severe floods, permanent stream-gauge installations are sometimes overtopped or washed away and the record is lost. For these reasons, very valuable information can be obtained by a field survey crew in the area of a storm flood immediately following a severe occurrence. In addition, data from instruments, such as weather radar, are often valuable in hydrological studies (3.7).

2.5.8.2 Bucket surveys of storm rainfall

Measurements of rainfall from private, non-standard raingauges, and estimates that can be made from various receptacles, such as pails, troughs and barrels (provided these can be verified to have been empty prior to the storm), can be used to augment rainfall data from the regular observing network. Eyewitness reports can be obtained of beginning and ending times of rainfall and of periods of very heavy rain. Care must be taken in interpretation of bucket-survey data, and where discrepancies exist between data from a bucket survey and the regular observation network. Greater weight should usually be given to the latter.

2.5.8.3 Weather-radar and satellite data

Data from weather radars and satellites are valuable in determining the intensity and areal distribution of rainfall and beginning and ending times of precipitation over a specific river basin. For record purposes, these data can be collected on photographic film or in digital form by a computer linked to the radar. These digitized data can be readily transmitted to forecast offices over computer networks.

2.5.8.4 Extreme river stages and discharges

Extreme events during floods and droughts should be documented at both regular gauging stations and at non-gauged locations.

High-water marks along rivers are useful in delineating flooded areas on maps, in the design of structures such as highway bridges, and for estimation of flood slopes. These marks, if taken carefully, may also be used with other data to compute the peak discharge of the stream by indirect methods (5.3.5).

Field surveys to measure minimum streamflow at non-gauged locations provide valuable data at a very economical cost. These measured discharges can be correlated with the simultaneous discharges at regular gauging stations to determine the low-flow characteristics at the ungauged sites.

2.5.8.5 Video imagery techniques

A video camera installation can provide valuable information about the conditions at a gauging site. The extent of ice cover, periods of backwater due to ice, etc., can be documented by a camera. This technique can also be used for remotely monitoring potential hazards, for example, risks due to avalanches.

Recently, video imagery-based approaches have been used to measure discharge by estimating surface velocities using particle image velocimetry methods The video data can be recorded on site, or, if real-time information is required, readily reported via some transmission facility.

2.6 MEASUREMENT OF PHYSIOGRAPHIC CHARACTERISTICS

2.6.1 General

The concepts discussed in this section cover two quite different physiographic characteristics: the location of the feature(s) under study, and their physical response to atmospheric events. By locating these features, it is possible not only to catalogue them, but also to determine their spatial distribution and the climate zone to which they belong.

The features themselves can be examined in terms of points, lines, areas or volumes depending on the relationship between a particular characteristic and the hydrological regime. For example, streamflow results from the transformation of climatic events (rainfall, snow melt) by the physical complex that comprises a drainage basin. The basin location partially determines the climatic characteristics, which are responsible for meteorological events that drive the hydrology. However, the basin's physical characteristics not only control the hydrological response to the meteorological events, but some characteristics, for example, orography and aspect, can also be causal factors in the determination of the basin's climate.

Physiographic characteristics are now commonly examined as layers of information within contemporary GIS. The physical response of a watershed to meteorological events can be analysed using hydrological and hydraulic models as well. The fundamental procedures presented in this section form the basis for computer-assisted data assembly and analysis.

2.6.2 Reference systems and data frameworks

Physiographic characteristics are but one component of geospatial information; that is, information pertaining to the character and location of natural and cultural resources and their relation to human activity. This information has become so important that the concepts of national and international spatial data infrastructure and framework data have been developed. Spatial data infrastructure can be considered as the technology, policies, criteria, standards and people necessary to enable geospatial data sharing throughout all levels of government, the private and non-profit sectors, and academia. It provides a base or structure of practices and relationships among data producers and users that facilitates data sharing and use. Framework data can be considered as a set of continuous and fully integrated geospatial data that provides context and reference information for the country or region. In general, this will consist of alignment data such as geodetic control, data on land features and form such as physiographic data, and conceptual data such as government units. A rigorous national data framework facilitates information exchange and significantly reduces duplication of effort. Framework data that will be of interest to hydrological analysis include geodetic control, elevation, orthoimagery, hydrography, transportation, government units and cadastral information (National Research Council, 1995).

Geodetic control is defined by using the international system of meridians and parallels divided into 360 degrees, with the zero meridian passing through Greenwich. This system is the most widely used. Its only disadvantage is that a degree in longitude varies from 111.111 km at the Equator to 0 at the Pole and represents 78.567 km at a latitude of 45° (a degree in latitude always measures 111.111 km). Local systems and other modes of projection are also in use, for example, the Lambert system. However, these cannot be recommended in an international guide. Furthermore, algorithms for converting geographic coordinates to local reference systems when this may be required are readily available.

Elevation or altitude is provided in relation to a given level or reference plane. While local reference data are sometimes used, until relatively recently mean sea level was the most commonly used vertical data. The widespread use of global positioning system observations led to the adoption of geocentric vertical (and horizontal) data in accordance with the world geodetic system, in preference to those based on mean sea level. The reference ellipsoid, WGS-84, or a national geocentric variation is therefore the preferred vertical reference. The fundamental requirement in any use of a coordinate system is that the data used must be specified.

The topography of a river basin may be represented in two different ways: as a digital elevation model or as a triangulated irregular network (TIN). The digital elevation model is a grid of elevation values that has regular spacing while TIN is a series of points linked into triangular surfaces that approximate the surface. The spacing of points in TIN are non-uniform, which allows points to be located on critical terrain features, roads or river banks. The accuracy of such digital terrain models depends on the source of the data, the point density and distribution, and other related data used in their development. Conventional contour maps may be prepared from a digital elevation model or TIN.

Orthophotos are images of the landscape from which features can be referenced to one another. They are digital images produced by processing aerial photography to geodetic control elevation data to remove all sources of distortion. The image has the properties of scale and accuracy associated with a map. Such images can be derived using airborne or satellite sensors.

The basic elements used in estimating physiographic parameters are rarely measured directly by the hydrologist, who essentially works with global positioning system data, orthophotos, maps, aerial photographs and satellite imagery. Therefore, the accuracy of the evaluation depends upon the accuracy of source materials.

2.6.3 **Point measurements**

The geometric point is defined here as a unique location on a line or within an area or volume. A point may be a physical element, such as the location of a measuring instrument or the outlet of a basin. It can also be an element of an area (plot of land) on which a given characteristic or set of characteristics is to be defined or measured. The physiographic characteristics attributed to a point may be simple or complex. An example of a simple characteristic of a point is its elevation, which is one of its unique identifiers in three-dimensional space. A more complex characteristic might be a description of the soil profile that underlies the point.

Applications of remote-sensing techniques, starting with aerial photography, has had the effect of expanding the notion of a point to an area (pixel), which may measure up to several square kilometres. Within their limits of accuracy, available techniques may not be able to distinguish between two points (for example, an instrument's lack of resolution), and a pixel might be taken to be a point.

The horizontal location of a point, that is, its position on the globe, is determined by a selected system of coordinates (2.6.2), which falls within the scope of geodesy and topography. A universal system has been invented to make the coding of a point in a catalogue explicit by indicating its geographical position. This is the GEOREP squaring system (UNESCO, 1974) for spatial representation of linear features. Other systems may locate points by their linear distances along a stream from a given origin, for example, mouth or confluence.

The physiographic description of a point covers its geometric properties (form, relief, slope, etc.) and its permanent physical properties (permeability, nature of rocks, soil structure, land-use type, etc.). The former are limited to the local slope, while the latter comprise a whole range of possible physical properties, expressed in scalar form for a point on a horizontal surface or in vectorial form for a profile, for example, geological core.

2.6.4 Linear measurements

Any physiographic element is linear if it can be represented by a line on a map or in space. In hydrology, three types of linear elements are common:
(a) Boundaries;
(b) Isopleths of a permanent feature, for example, contours;
(c) Thalwegs.

The first two types are linked to areal aspects, which will be examined later.

The thalweg is itself to be considered not only as represented in horizontal projection and longitudinal profile, but also by the way in which it combines with other thalwegs to form a drainage network, which has its own physiographic characteristics. Some drainage network characteristics are linear, for example, the bifurcation ratio, while others are areal in nature, such as the drainage density.

2.6.4.1 The stream

A stream in horizontal projection may be represented, if the scale of the diagram is suitable, by two lines representing its banks. From these two lines, an axis can be drawn equidistant to the two banks. The axis may also be defined as the line joining the lowest points on successive cross-sections. In fact, these elements, the visible banks and the lowest points, are not always very clear, and the map scale does not always permit the banks to be featured properly. Mapping, thus, is reduced to representing a stream by a line.

Lengths along a river are measured by following this line and by using a curvometer. The accuracy of the determination depends on the map's scale and quality, as well as on the curvometer's error, which should not exceed six per cent for a distance on the map of 10 cm or 4 per cent for 100 cm and 2 per cent beyond. Many hydrological features can be derived directly from the orthoimagery or digital terrain data with the aid of GIS (2.6.7).

The axis of a stream is rarely straight. When it comprises quasi-periodic bends, each half-period is called a meander. The properties and dimensions of meanders have been thoroughly studied by geographers and specialists in river hydraulics.

2.6.4.2 The drainage network

In a basin, streams are organized to form a drainage network. In a network, all streams are not the same size, and several systems have been proposed for classifying them. Several stream classification systems are in use in various countries and current GIS provide for automatic stream classification according to schemes devised by Horton, Schumm, Stahler, Shreve and others. The best known schemes is Horton's, in which any elementary stream is said to be of order 1, any stream with a tributary of order 1 is said to be of order 2, and any stream with a tributary of order x is said to be of order $x + 1$. At a confluence, any doubt is removed by giving the higher order to the longest of the tributaries forming it (Figure I.2.15) (Dubreuil, 1966). This introduces some inaccuracy that was avoided by Schumm by systematically giving order x to the reaches formed by two tributaries of order $x – 1$ (Figure I.2.16). The main source of error in such evaluations is to be found in the mapping of the streams, where the definition of the smallest streams is often rather subjective.

Of the linear characteristics of the drainage network that are measurable on a map, the confluence ratio R_c and the length ratio R_l are based on Horton's laws and have been verified for Horton's classification. Given that N_x is the number of streams of order x, and $lm_x = \sum l_x / N_x$ is the mean length of the streams of order x, these laws are expressed by the following relationships:

$$N_x = R_c * N_{x+1} \qquad (2.9)$$

and

$$lm_x = R_l * lm_{x-1} \qquad (2.10)$$

which form geometric progressions and may be written as follows:

$$N_x = N_1 * R_c^{1-x} \qquad (2.11)$$

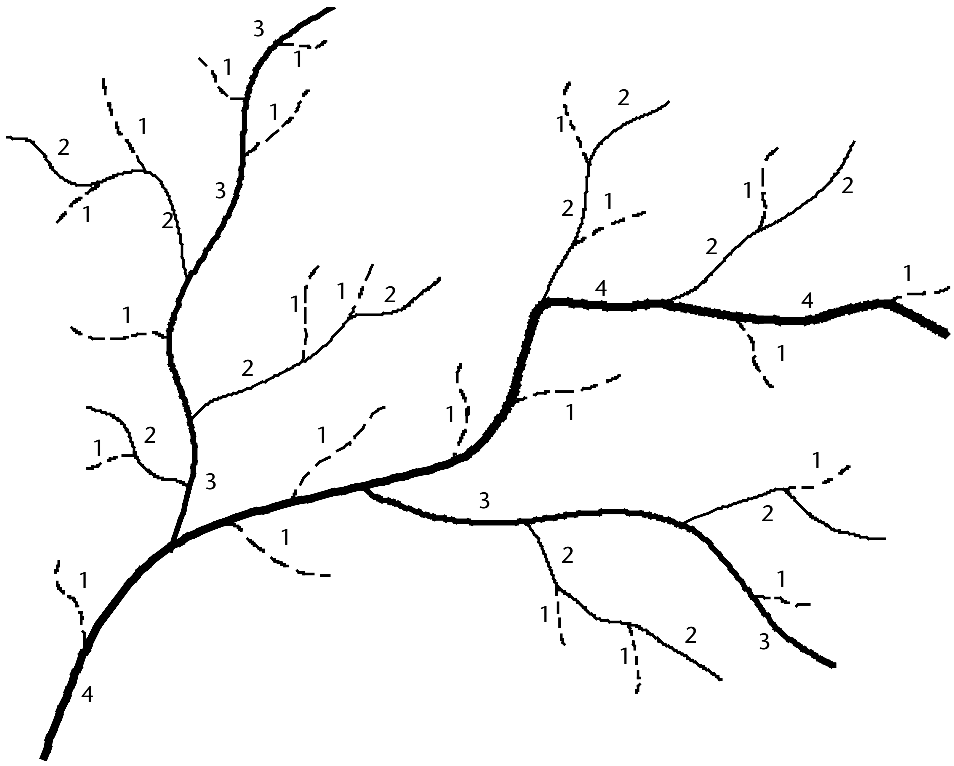


Figure I.2.15. Horton's classification

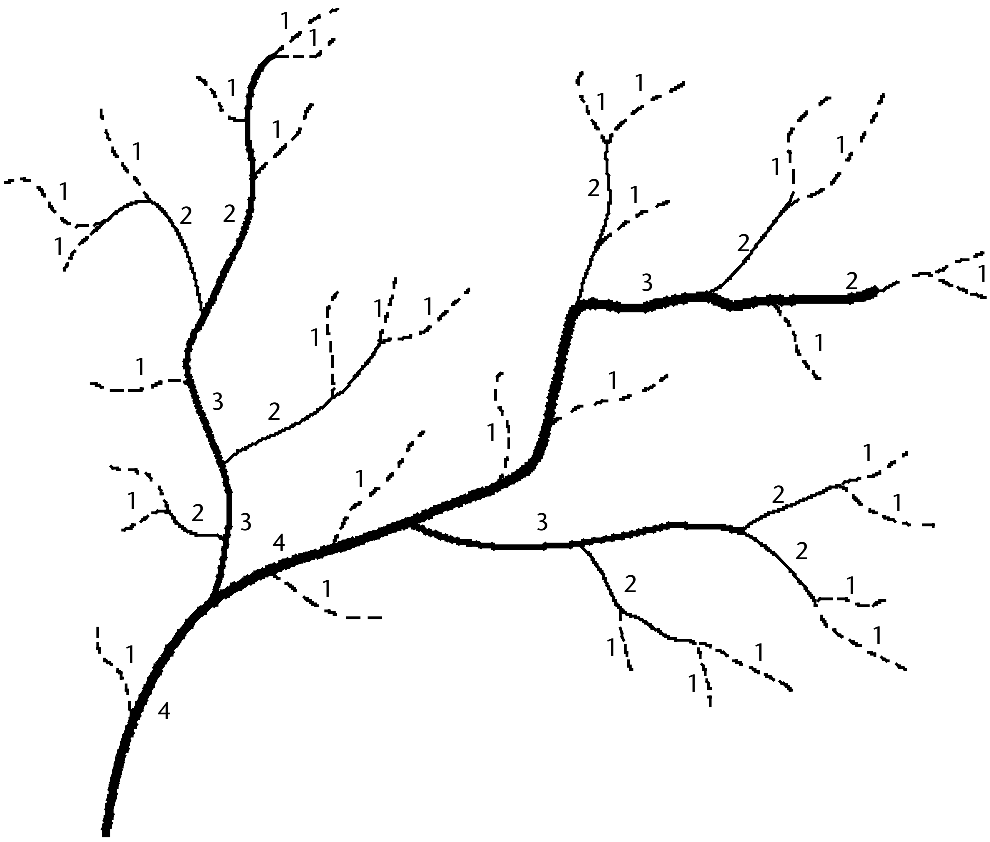


Figure I.2.16. Schumm's classification

and

$$lm_x = R_l^{x-1} * lm \qquad (2.12)$$

where R_c and R_l are calculated as the slopes of the straight lines adjusted to the graph points ($\log N_x$, x) and ($\log lm_x$, x) and x is the basin order.

2.6.4.3 Stream profile

The stream profile is the variation in elevation of the points of the stream thalweg as a function of their distance from the origin, which is generally taken as the confluence of the stream with a larger stream or as its mouth. On such a profile, a certain number of topographical features are to be found, such as high points (thresholds), hollows between two thresholds (pools), rapids, waterfalls and changes of slope that frequently mark the boundary between two reaches with different geologic controls (Figure I.2.17).

The average slope of a whole stream is the difference in elevation between its highest point and its confluence or mouth divided by its total length. This notion is simple, but not very useful. On the other hand, knowledge of the slopes of the successive stream reaches is essential for most runoff and hydraulic models.

The profiles of the main stream and of various tributaries in the same basin can be represented on the same diagram. Figure I.2.18 shows examples of stream profiles of the Niger river at Koulikoro and of its main tributaries and sub-tributaries. Such a diagram gives a synthesized view of the variation in slope of the drainage network's elements.

2.6.4.4 Cross-section

The profile of the valley taken perpendicular to a stream's axis is called a cross-section, and a series of these is valuable information for the development of streamflow models. Cross-sections are used in several types of calculations, and the way in which they are established may depend on the use to which they will be put.

An important particular case is the calculation of flow for a discharge measurement, in which elevation is expressed as a depth and is obtained by sounding (5.3). Cross-sections are usually obtained by making normal topographical measurements during the lowest flows.

2.6.4.5 Physical characteristics

The type of material in the stream bed (particularly its cohesiveness), the type and amount of vegetation in and along the stream, and the roughness of the bed, which depends on the longitudinal and transverse distributions of the former, comprise the primary physical characteristics of a stream. Roughness is incorporated in the flow calculations

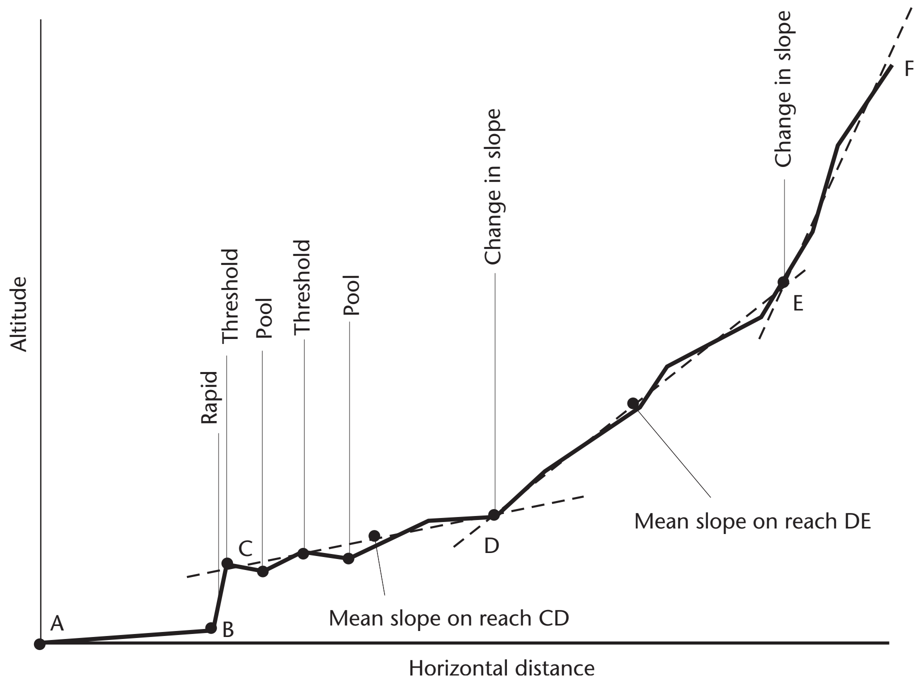


Figure I.2.17. Stream profile

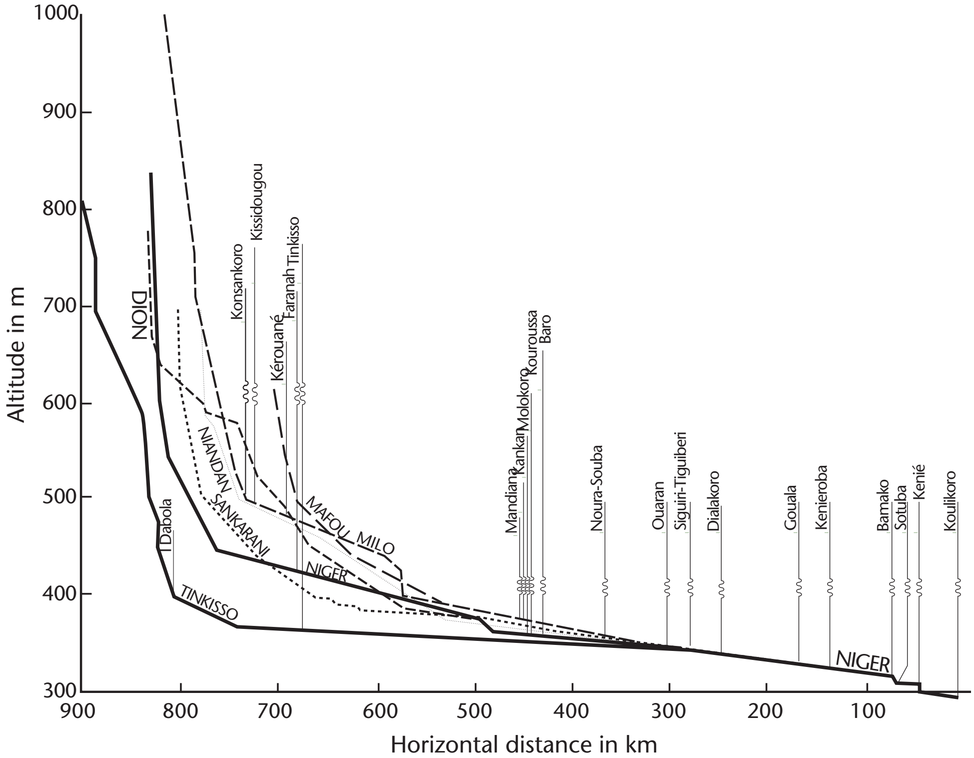


Figure I.2.18. Profile of the Niger river and its tributaries

by the indirect method (5.3.5) and in runoff models (Volume II, Chapter 6).

2.6.5 Area measurements

2.6.5.1 The basin

The basin is defined as the area that receives precipitation and, after hydrological processes resulting in losses and delays, leads it to an outflow point. The watershed boundary, the basin's perimeter, is such that any precipitation falling within it is directed towards the outflow, whereas any precipitation falling outside drains to a different basin and outflow. In some cases, it may not be easy to determine the basin boundary, for example, when the head of the main stream is formed in a very flat-bottomed valley or a marshland. The watershed is usually defined by using contour maps or aerial photographs.

The basin perimeter is measured in a GIS (2.6.7) or with a curvometer. The measured perimeter is a function of the scale and accuracy of the maps or photographs, the quality of the curvometer, and the care taken in its use (Figure I.2.19). The ultimate use that will be made of the measurement should determine the accuracy to which it is measured.

The basin area is determined in a GIS or measured by planimetry by following the boundaries established as described above.

The basin's shape is characterized by comparing its perimeter with that of a circle having the same area. If A is the basin area and P its perimeter, both measured according to the above rules and expressed in compatible units, then the ratio of the

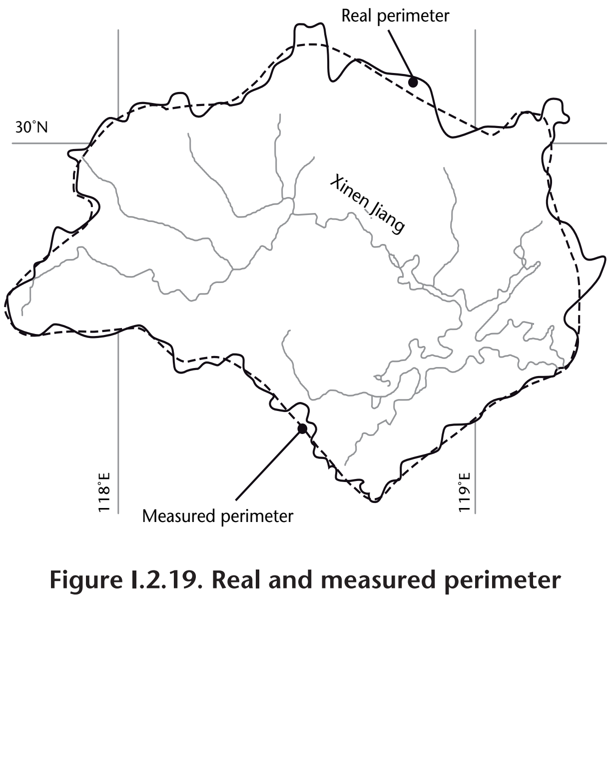


Figure I.2.19. Real and measured perimeter

two perimeters is called the Gravelius coefficient of compactness, which is given by:

$$C = 0.282\, P\, A^{1/2} \tag{2.13}$$

The notion of an equivalent rectangle is also linked to the basin's shape, and permits the definition of a particular slope index. The equivalent rectangle has the same area and the same Gravelius coefficient as the basin. The length of this rectangle is:

$$L = A^{1/2} \frac{C}{1.128} \left[1 + \sqrt{1 - 1.272 / C^2} \right] \tag{2.14}$$

The drainage density is defined as the total length of streams of all orders contained in the basin's unit area:

$$D_d = (\sum L_x)/A \tag{2.15}$$

where L_x is the total length of the streams of order x. In common practice, the lengths are expressed in kilometres and the areas in square kilometres.

The basin relief, shown on maps by contours, can be described by the hypsometric distribution or the hypsometric curve. Figure I.2.20 shows a representation of relief and drainage network. The elevation ranges are shown by different marking.

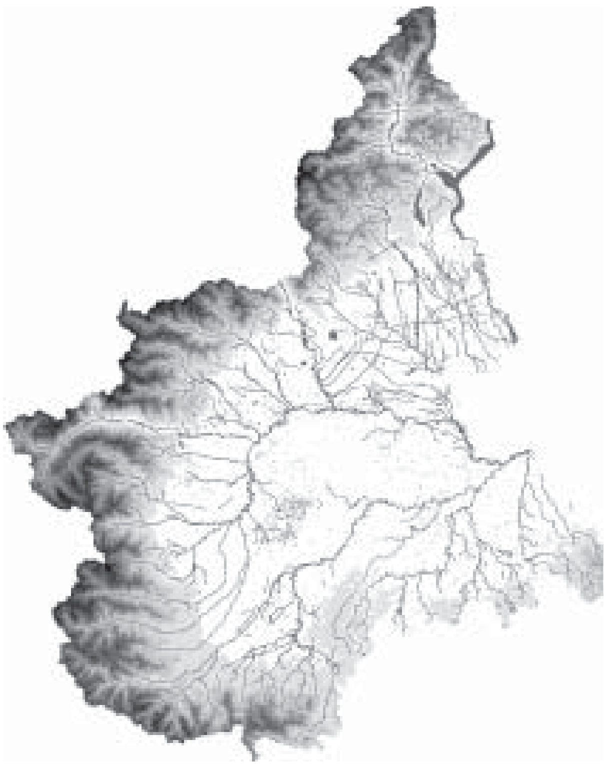


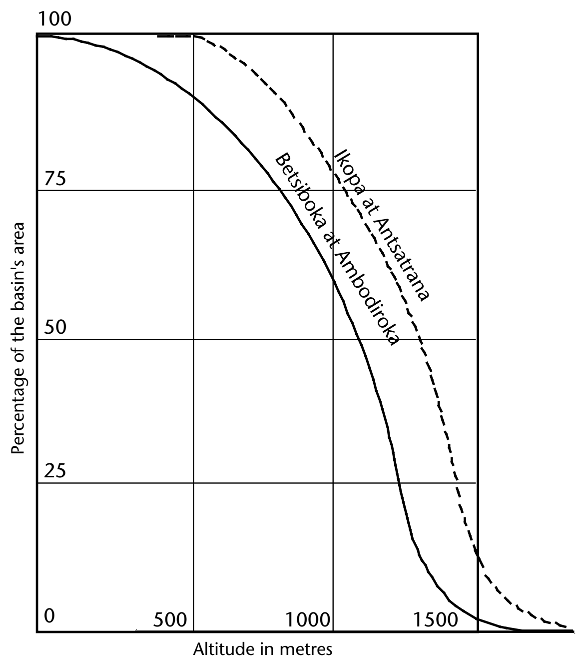
Figure I.2.20. Relief and drainage network
(Courtesy ARPA-Piemonte)

The hypsometric distribution gives the percentage (or fraction) of the basin's total area that is included in each of a number of elevation intervals. The hypsometric curve shows, on the ordinate, the percentage of the drainage area that is higher than or equal to the elevation that is indicated by the corresponding abscissa (Figure I.2.21). In practice, the cumulative distribution of area is obtained in a GIS or by planimetric calculation of successive areas between contours of elevation beginning with the basin's lowest point.

It is possible to calculate the basin's mean elevation by dividing the area under the hypsometric curve by the length of the ordinate corresponding to the whole basin.

The basin slope can be represented by several indices. The oldest, and perhaps still the most widely used, is the basin's mean slope S_m. It is determined from the basin contours by the formula:

$$S_m = z \sum l/A \tag{2.16}$$



Ikopa at Antsatrana		Betsiboka at Ambodiroka	
300–400 m ...	0.01	40–300 m ...	0.03
600–900 m ...	0.14	300–800 m ...	0.10
900–1 200 m ...	0.23	600–900 m ...	0.18
1 200–1 500 m ...	0.43	900–1 200 m ...	0.37
1 500–1 800 m ...	0.12	1 200–1 500 m ...	0.30
1 800–2 100 m ...	0.01	1 500–1 800 m ...	0.02

Figure I.2.21. Hypsometric curves
(Courtesy ARPA-Piemonte)

where z is the contour interval, $\sum l$ is the total length of all contours within the basin, and A is the basin's area. The difficulty and main source of error in estimating this characteristic lie in the measurement of $\sum l$. The contours are almost always very tortuous and their real length is not really characteristic of the role they play in calculating the index. Therefore, it may be necessary to smooth the irregularities keeping in mind the final results may be somewhat inconsistent and variable.

A mean slope can also be estimated by taking the basin's total difference in elevation and by dividing it by one of its characteristic dimensions. However, the distribution of slopes in the basin is neglected by this approach. One way of avoiding this is to derive the slope index from the hypsometric curve, which is a synthesis of the relief delineated by the contours, and to weigh the areal elements corresponding to the various elevation intervals by a non-linear function of the mean slope in each interval. Roche's slope index, also called the index of runoff susceptibility, meets these conditions. The notion of the equivalent rectangle (equation 2.14) is applied to each contour to transform geometrically the contours into parallel straight lines on the rectangle representing the entire basin (Figure I.2.22). If a_i and a_{i-1} are the elevations of two successive contours and x_i is the distance separating them on the equivalent rectangle, the mean slope between these two contours is taken to be equal to $(a_i - a_{i-1}) / x_i$, and the slope index is written by designating as $\tilde{n}_i$ the fraction of the basin's total area included between a_i and a_{i-1}:

$$I_\pi = \sum (\tilde{n}_i(a_i - a_{i-1}) / L)^{1/2} \qquad (2.17)$$

The Roche slope index is as follows:

Basin	*Length of equivalent rectangle*	*Slope index*
Betsiboka at Ambodiroka	238 km	0.078
Ikopa at Antsatrana	278 km	0.069

When basins have a very low slope, for example, in the interior plains of North America, there may be closed sub-basins having no outlet to the main stream or significant portions of the basin that contribute to streamflow very infrequently. Under these circumstances the concept of an effective drainage area may be used. This is customarily defined as the area that would contribute to streamflow in a median year. Establishing the effective drainage area for a basin may require significant cartographic and hydrological analysis.

A basin's physical characteristics are essentially the soil types, the natural plant cover or artificial cover (crops), the land cover (for example, lakes, swamps, or glaciers), and the type of land use (for example, rural or urbanized areas, lakes, or swamps). They may also be expressed in terms of the basin's reaction to precipitation, this is, classes of permeability. These physical characteristics may be assembled as layers within a GIS.

The quantification of these characteristics requires definition of criteria and procedures for delineating

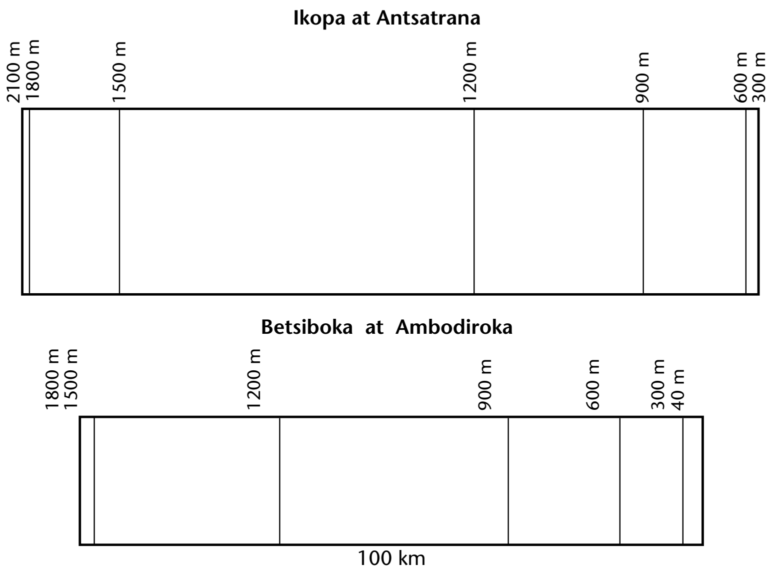


Figure I.2.22. Equivalent rectangles

the areas meeting these criteria. It then remains only to measure each of these areas and to express each as a percentage (or fraction). The tools for determining such distributions include GIS, normal and/or specialized cartography, aerial photography and remote-sensing with relatively fine resolution (pixels not to exceed some hundreds of square metres).

2.6.5.2 The grid

The formation of physiographical data banks, especially for the development of rainfall-runoff models with spatial discretization, leads to the division of the basin area based on systematic squaring or griding. Depending on the objective, the grid size may be larger or smaller, and may be measured in kilometres (1 or 5 km^2) or based on the international geographical system (1′ or 1° grid). GIS (2.6.7) have made interchanging between gridded and ungridded data a simple task once the initial databases have been assembled.

2.6.6 Volumetric measurements

Volumetric measurements pertain primarily to the definition of water and sediment storage. Evaluation of groundwater storage is covered by hydrogeology. It therefore will not be discussed here, nor will the estimation of sediment deposited on the soil surface. Surface storages are generally either the volumes of existing lakes or reservoirs, for which bathymetric methods are used, or the volumes of reservoirs that are being designed, for which topographical methods are used.

2.6.6.1 Bathymetric methods

Ordinary maps rarely give bathymetric data on lakes and reservoirs. The volume of an existing reservoir, therefore, has to be measured by making special bathymetric readings. Usually, this is done from a boat by using normal methods for sounding and for positioning the boat. The depths should be referenced to a fixed datum and a stage gauge or a limnigraph so that variations in stage can be monitored.

Depth measurements can be used to plot isobaths, and the reservoir's volume above a reference plane can be calculated through double integration (generally graphical) of the isobath network. One application of this method is sedimentation monitoring in a reservoir.

2.6.6.2 Topographical methods

Once the site of a dam has been fixed, the calculation of the reservoir's efficiency and management requires knowledge of the curve of volume impounded as a function of the reservoir's stage (stage-volume curve). To determine this relationship, ground-surface-elevation contours are needed throughout the area to be occupied by the future impoundment. This requires maps or topographical plans of the area on scales of between 1/1 000 and 1/5 000. If these are not available, maps on a scale of 1/50 000 can be used for preliminary design, but a topographical survey on an appropriate scale will be needed subsequently.

By using the contour map, planimetric measurements are made, in a GIS or manually, of the areas contained within the contours with the hypothetical reservoir in place. A plot of these areas versus their related elevations is known as a stage-area curve. The stage-volume curve is computed from the stage-area curve by graphical integration.

2.6.7 Geographical Information Systems

GIS are now ubiquitous in the fields of operational hydrology and water resources assessment. Many aspects of data collection and interpretation can be facilitated by means of GIS.

In network planning and design, the ability to map quickly and display surface water and related stations enables a more effective integration to take place. Network maps, showing basins or stations selected according to record quality, watershed, or operational characteristics, can be used for both short-term and long-term planning. The essential features of complex networks can be made very clear.

GIS techniques are being incorporated in hydrological models for the purpose of extracting and formatting distributed watershed data. Used in conjunction with digital elevation models or TINs (2.6.2), complete physiographic and hydrological depiction of basins can be readily accomplished.

Runoff mapping and interpolation is being carried out using GIS routines in many countries. The efficiency of handling large volumes of data means that more comprehensive and detailed maps, isolines and themes can be prepared. This represents a significant improvement to water resources-assessment technology, as map preparation is often time-consuming and expensive.

The interpretation of real-time data can also be facilitated through GIS. The thematic mapping of stations reporting over threshold amounts or digital indications of rainfall would obviously be very useful to both operational hydrology and forecasting agencies.

GIS systems are now available for standard computers in practical, low-cost formats. The main cost factor now resides in the areas of database compilation, and training and updating of technical staff.

2.6.8 Emerging technologies

The subsequent chapters of this Volume of the Guide deal with proven technologies that are commonly used in many parts of the world. However, as indicated above, new technologies are continuously evolving. This section provides some insight into several of these so that Hydrological Services may be kept aware of their possibilities.

2.6.8.1 Remote-sensing

In the field of hydrological measurements, two kinds of remote-sensing techniques are commonly used: active (by emission of an artificial radiation beam toward the target and analysis of the target response), or passive (by analysis of the natural radiation of an object).

In active methods, radiation may be high-frequency electromagnetic (radar) or acoustic (ultrasonic devices). The apparatus may be installed on the ground (radar, ultrasonic), on airplanes, or on satellites (radar). Active remote-sensing is usually done on an areal basis, but may also be used for point-oriented measurements (ultrasonic).

In passive methods, the radiation is electromagnetic (from infra-red (IR) to violet, and rarely ultraviolet). Most current applications are made by means of a multi-spectral scanner, which may be airborne, but is more frequently carried on a satellite. Passive sensing is always areal.

Radars are now used for quantitative precipitation estimates over a given area. Snow-water equivalent can be determined by measuring the natural gamma radiation from potassium, uranium and thorium radioisotopes in the upper 20 cm of soil under bare ground conditions and with the snowpack. Observations are made from a low-flying aircraft. Data are collected on a swath about 300 m wide and 15 km long. Results will be affected by ice lenses or liquid water in the snowpack, ground ice or standing water (Carroll, 2001). Microwave sensors, both airborne and satellite, have been used as well to monitor snowpack properties. RadarSat active radar has also been used to map the areal extent of wet snow.

Airborne optical devices (Lidar) are now used to determine topography more rapidly and, often, more accurately and at lower cost than conventional aerial photography. The resulting digital elevation model has applications in hydraulic and hydrological modelling and in determining glacier mass balance. Satellite Lidar altimetry has been used to obtain very good topography for military purposes and in research applications, but has not yet been commercialized. In the absence of national topographic data, the low-resolution global digital elevation model GTOPO30 with a horizontal grid spacing of 30 arc seconds (roughly 1 km) may be considered. The vertical accuracy of the data is about 30 m. This digital elevation model is also linked to the HYDRO1k package which provides a suite of six raster and two vector data sets. These data sets cover many of the common derivative products used in hydrological analysis. The raster data sets are a hydrologically correct digital elevation model, derived flow directions, flow accumulations, slope, aspect and a compound topographic (wetness) index. The derived streamlines and basins are distributed as vector data sets.

A further existing topographic data option is the 3 arc-second (90 m) digital elevation model produced by the Shuttle Radar Topography Mission. The data for most of the coverage area have been processed to level 1, which provides for an absolute horizontal accuracy of 50 m and a vertical accuracy of 30 m. The level 2 digital elevation model, currently available only for the United States, has a horizontal accuracy of 30 m and vertical accuracy of 18 m.

Other uses of remote-sensing in hydrology include sensing of near-surface soil moisture using airborne natural gamma or satellite passive microwave techniques and measurement of land surface temperature as a precursor to determining evapotranspiration. Leaf area index measurements use may also lead to remote-sensing of evapotranspiration. Remote-sensing of water quality also offers considerable promise as new satellites and sensors are developed. Water bodies that are affected by suspended sediment, algae or plant growth, dissolved organic matter, or thermal plumes undergo changes in spectral or thermal properties that may be detected by airborne or satellite sensors (UNEP/WHO, 1996). Some use has been made in the measurement of water body areas and the extent of flood inundation using RadarSat active radar. Aside from the requirement to calibrate airborne or satellite sensors, there is also a need to ground-truth the remotely sensed data to ensure that remotely sensed values represent in situ values.

2.6.8.2 Hydroacoustic methods

Hydroacoustic methods hold considerable promise for hydrological data acquisition. Acoustic signals may be used to identify the interface between two dissimilar media or to explore the characteristics of a single medium. For example, echo sounders are used to define the streambed in hydrographic surveys or to sense the distance to the water surface when mounted in or above a stream. Results can be very satisfactory provided careful attention is paid to calibration of the instrument. Acoustic current meters that determine water velocity by measuring the Doppler shift of acoustic energy reflected from water-borne particles have been used for a number of years.

The 1990s saw the development of the Acoustic Doppler Current Profiler (ADCP), an instrument that uses acoustic energy to determine streamflow from a moving boat. The instrument consists of four orthogonal ultrasonic transducers fixed to a moving boat. As the boat traverses a river the instrument measures the frequency shift of the reflected signals and uses trigonometry to produce velocity vectors in uniformly spaced volumes known as depth cells. The velocity of the boat is removed in computer processing and, with the channel geometry also defined by the instrument, the streamflow along a river transect can be calculated. This technique has been used successfully to measure relatively large streams. More recently, efforts have been directed to the measurement of smaller streams (under 2 m depth) using hand-held or in situ instruments.

Acoustic devices have also been developed to examine lake dynamics or to determine the density and material characteristics of bottom and sub-bottom sediments. Ultrasonic flowmeters are reviewed in Chapter 5.

2.6.8.3 Risk reduction for personnel

There are inherent dangers to personnel involved in acquiring hydrological data under difficult conditions. These dangers are perhaps best exemplified by the challenge of measuring streamflow under flood conditions. High velocities, debris or ice may threaten the life of persons attempting to make the measurement. Efforts are therefore underway to automate the measurement process through use of robotics and other procedures. One early approach to improved safety was the development of streamgauging cableways that could be operated from the river bank. Another was the moving boat method, which reduces the time required for a discharge measurement, but still requires exposing personnel to the hazard.

One current concept calls for an automated, unmanned boat equipped with an Acoustic Doppler Current Profiler the position of which is monitored by use of the global positioning system. Measurements can therefore be made under high hazard conditions with minimum exposure of personnel to the hazard. Another approach uses a hand-held radar to measure surface velocities and, where channels are unstable, ground-penetrating radar to define the channel cross-section. The radar device produces an accurate surface velocity, which must then be related to mean velocity, while the ground-penetrating radar moving along a bridge or cableway produces an accurate cross-section.

Other risk reduction efforts include the decommissioning of water-level sensors based on mercury manometers and the increased use of satellite telephones as a means of maintaining contact with field parties in remote areas.

2.6.9 Staff training

Whatever the level of technical sophistication of a data-collection authority, the quality of its staff will always remain its most valuable resource. Careful recruitment, training and management is the key to attaining and maintaining the appropriate personnel.

WMO has published a set of *Guidelines for the Education and Training of Personnel in Meteorology and Operational Hydrology* (WMO-No. 258). UNESCO has published a document on *Curricula and Syllabi in Hydrology* (UNESCO, 1983). With respect to data collection and processing, employee education, although costly and time-consuming, can be a sound investment that results in greater productivity and effectiveness. A carefully structured training programme is essential for all personnel engaged in data collection because they are in a strong position to influence the standard of the final data. Formal training should aim at providing both a general course in first principles, plus training modules to teach in-house procedures. All material should be relevant and current. The Canadian hydrometric technician career development programme (HOMS component Y00.0.10) provides one national example (WMO, 2000). Volume II, Chapter 2, provides additional information on different aspects of training in hydrology.

Where processing is not carried out by the data collector, it is important that data processors be trained in data-collection techniques to ensure that data are processed according to the intent of the collector. It is a good practice to give processing staff periodic field experience to build a physical association with the data and their origins. Such knowledge on the part of the processor can allow interim interpretations of incorrectly presented data, pending confirmation from the collector. It is essential to establish the principle that the person collecting the data has the primary responsibility for its quality. One method of honouring this principle is to involve the collector in the processing as much as possible, and to ensure that feedback is obtained by returning the published data to the collector for assessment. At the processing stage, staff should recognize that they also have a responsibility to maintain the quality and integrity of the data.

Data processing is often routine in nature and well suited to the application of automation and technology. For this reason, it is important that special attention be given to the care of human resources, and that the system be structured to foster interest, involvement, professionalism and a sense of achievement. Data-processing staff should be given the opportunity to contribute ideas that may increase the effectiveness of the processing system.

Staff safety is also an integral component of any profession, and the duties undertaken by data collectors and processors require the establishment of safety standards. These are primarily discussed in Chapter 8. However, the possibility of repetitive strain injury in data-processing staff can often be caused by routine and the repetitive nature of some aspects of their jobs. This problem should be addressed from both a staff safety and a management point of view.

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CHAPTER 3

PRECIPITATION MEASUREMENT

3.1 GENERAL REQUIREMENTS: ACCURACY AND PRECISION

The total amount of precipitation reaching the ground during a stated period is expressed as the depth to which it would cover a horizontal projection of the Earth's surface, if any part of the precipitation falling as snow or ice were melted. Snowfall is also measured by the depth of fresh snow covering an even, horizontal surface.

The primary aim of any method of precipitation measurement is to obtain representative samples of the fall over the area to which the measurement refers. There is a critical need in hydrology for accurate measurement of precipitation. Therefore, for raingauges the choice of site, the form and exposure of the measuring gauge, the prevention of loss by evaporation, and the effects of wind and splashing are important considerations. More complex methods such as the use of weather radar and satellites require detailed understanding of error characteristics. This chapter discusses the facets of precipitation measurement that are most relevant to hydrological practice. A more general discussion of the topic can be found in the *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8).

3.2 RAINGAUGE LOCATION

In a perfect exposure, the catch of the raingauge would represent the precipitation falling on the surrounding area. However, this is difficult to attain in practice because of the effect of the wind. Much care has to be taken in the choice of the site.

Wind effects are of two types: the effects on the gauge itself, which generally reduce the amount of water collected, and the effects of the site on the wind trajectories, which are frequently more important and can give rise to either an excess or a deficiency in measured precipitation.

The disturbance created by an obstacle depends on the ratio of the obstacle's linear dimensions to the falling speed of precipitation. This effect is reduced, if not entirely overcome, by choosing the site so that the wind speed at the level of the gauge orifice is as small as possible, but so that there is not any actual blocking of precipitation by surrounding objects, and/or by modifying the surroundings of the gauge so that the airflow across the orifice is horizontal. All gauges in any area or country should have comparable exposures, and the same siting criteria should be applied to all.

The gauge should be exposed with its orifice remaining horizontal over ground level.

Where possible, the gauge site should be protected from wind movement in all directions by objects, such as trees and shrubs, of as nearly uniform height as possible. The height of these objects above the orifice of the gauge should be at least half the distance from the gauge to the objects, but should not exceed the distance from the gauge to the objects (to avoid interception of precipitation that should reach the gauge). The ideal situation is to have the angle from the top of the gauge to the top of the encircling objects between 30° and 45° to the horizontal (Figure I.3.1).

Objects such as windbreaks, consisting of a single row of trees, should be avoided as protection for gauges, as they tend to increase turbulence at the gauge site. Isolated or uneven protection near the gauge should also be avoided because of variable and unpredictable effects on the gauge catch. When adequate protection from the wind is not possible, individual objects should not be closer to the gauge than a distance equal to four times their height. Subject to these limitations, a site that is sheltered from the full force of the wind should be chosen to avoid wind-induced measurement errors. Caution

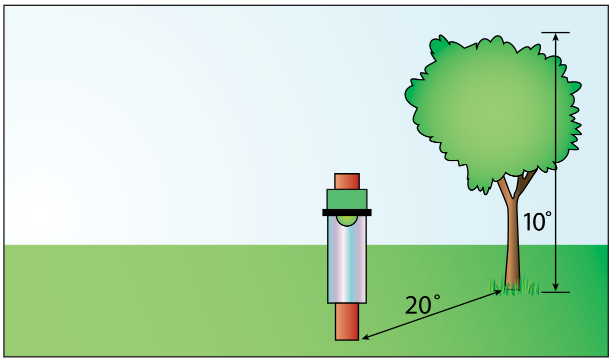


Figure I.3.1. Positioning of raingauge

should always be exercised, so that the site chosen does not produce significant disturbances in the wind. Sites on a slope, or with the ground sloping sharply away in one direction, especially if this direction is the same as the prevailing wind, should be avoided.

The ground surrounding the gauge can be covered with short grass or be of gravel or shingle, but a hard flat surface, such as concrete, gives rise to excessive splashing.

The height of the gauge orifice above the ground should be as low as possible because the wind velocity increases with height, but it should be high enough to prevent splashing from the ground. A height of 30 cm is used in many countries, in those areas that have little snow and where the surroundings are such that there is no risk of the ground being covered by puddles, even in heavy rain. Where these conditions are not satisfied, a standard height of 1 m is recommended.

In very exposed places, where there is no natural shelter, it has been found that better results can be obtained for liquid precipitation if the gauge is installed in a pit, so that the gauge rim is at ground level (Figure I.3.2). A strong plastic or metal anti-splash grid should span the pit with a central opening for the gauge funnel. The anti-splash grid should be composed of thin slats about 5 to 15 cm deep, set vertically at about 5 to 15 cm spacing in a square symmetric pattern. The area surrounding the gauge should be level and without unusual obstructions for at least 100 m in all directions.

An alternative installation, which is not quite so effective, is to install the gauge in the middle of a circular turf wall. The inner wall surface should be vertical with a radius of about 1.5 m. The outer surface should slope at an angle of about 15° to the horizontal. The top of the wall should be level with the gauge orifice.

Provision should be made for drainage. The pit gauge has been developed to measure liquid precipitation and should not be used for snowfall measurements.

An alternative way of modifying the surrounding of the gauge is to fit suitably shaped windshields around the instrument. When properly designed, these enable much more representative results to be obtained than with unshielded gauges fully exposed to the wind. An ideal shield should:

(a) Ensure a parallel flow of air over the aperture of the gauge;
(b) Avoid any local acceleration of the wind above the aperture;
(c) Reduce to the degree possible the speed of the wind striking the sides of the receiver. The height of the gauge orifice above the ground is then much less important;
(d) Prevent splashing towards the aperture of the receiver. The height of the gauge orifice above the ground is then much less important;
(e) Not be subject to capping by snow.

Precipitation in the form of snow is much more subject to adverse wind effects than is rainfall. In exceptionally windy locations, the catch in a gauge, with or without a windshield, may be less than half the actual snowfall. Sites selected for measurement of snowfall and/or snow cover should, as far as possible, be in areas sheltered from the wind. Windshields attached to the gauges have been shown to be quite effective in reducing precipitation catch errors due to wind, especially for solid precipitation. No shield yet developed, however, will entirely eliminate wind-induced measurement errors.

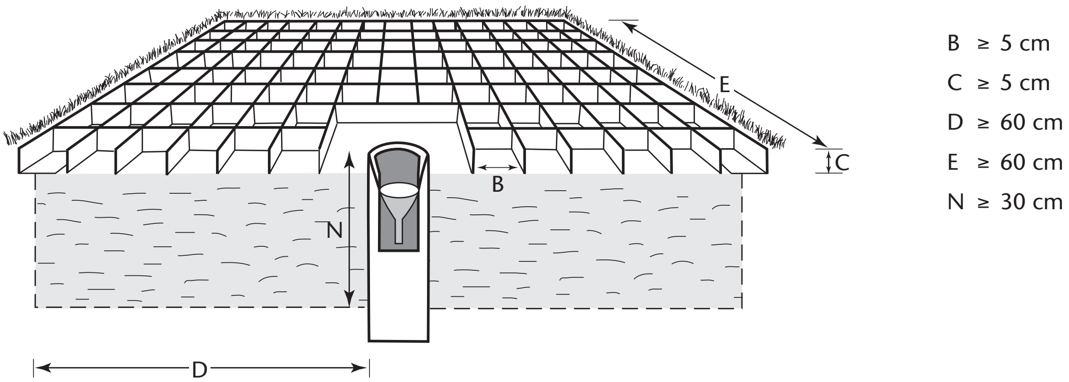


Figure I.3.2. Pit gauge for the measurement of liquid precipitation

3.3 NON-RECORDING RAINGAUGES
[HOMS C27]

3.3.1 General

The non-recording raingauges used by most Hydrological and Meteorological Services for official measurements generally consist of open receptacles with vertical sides, usually in the form of right cylinders. Various sizes of orifice and height are used in different countries and, therefore, measurements are not strictly comparable. The depth of precipitation caught in a gauge is measured by means of a graduated flask or dipstick. In gauges having other than vertical sides, the measurement is made either by weighing or measuring the volume of the contents, or by measuring the depth with a specially graduated measuring stick or scale.

3.3.2 Standard raingauges

The ordinary raingauge used for daily readings usually takes the form of a collector above a funnel leading into a receiver (Figure I.3.3). The size of the opening of the collector is not important. A receiving area of 1 000 cm^2 is used in some countries, but an area of 200 to 500 cm^2 will probably be found most convenient. The area of the receiver may be made to equal 0.1 of the area of the collector. Whatever size is chosen, the graduation of the measuring apparatus must be consistent with it. The most important requirements of a gauge are as follows:

Figure I.3.3. Ordinary raingauge

(a) The rim of the collector should have a sharp edge and should fall away vertically inside and be steeply bevelled outside. The design of gauges used for measuring snow should be such that errors due to constriction of the aperture, by accumulation of wet snow about the rim, are small;
(b) The area of the aperture should be known to the nearest 0.5 per cent and the construction should be such that this area remains constant;
(c) The collector should be designed to prevent rain from splashing in or out. This can be done by having the vertical wall sufficiently deep and the slope of the funnel sufficiently steep (at least 45°);
(d) The receiver should have a narrow neck and should be sufficiently protected from radiation to minimize loss of water by evaporation;
(e) When a part of precipitation comes in the form of snow, the collector should be deep enough to store the snowfall that can be expected during at least one day. This is also important to avoid the snow drifting out of the collector.

Raingauges for use at places where only weekly or monthly readings are taken should be similar in design to the type used for daily measurement, but with a receiver of larger capacity and stronger construction.

3.3.3 Storage raingauges

Storage raingauges are used to measure total seasonal precipitation in remote, sparsely inhabited areas. These gauges consist of a collector above a funnel, leading into a receiver large enough to store the seasonal catch. The criteria for exposure and shielding given in previous sections should also be considered in the installation of these gauges.

In areas where heavy snowfall occurs, the collector must be placed above the maximum expected depth of snow cover. This may be accomplished by mounting the entire gauge on a tower or by mounting the collector on a 30-cm diameter steel pipe of sufficient length to place its catch ring above the maximum accumulated snow.

An antifreeze solution is placed in the receiver to convert the snow that falls into the gauge into a liquid state. A mixture of 37.5 per cent of commercial-grade calcium chloride (78 per cent purity) and 62.5 per cent water by weight makes a satisfactory antifreeze solution. Alternately, an ethylene glycol solution can be used. While more expensive, the ethylene glycol solution is less corrosive than calcium chloride and gives protection over a much wider range of dilution caused by ensuing precipitation. The volume of the solution placed in the receiver should not exceed one third the total volume of the gauge.

An oil film should be used in the gauge to prevent loss of water by evaporation. An oil film about 8 mm thick is sufficient. Low viscosity, non-detergent motor oils are recommended. Transformer and silicone oils have been found unsuitable.

The seasonal precipitation catch is determined by weighing or measuring the volume of the contents of the receiver. The amount of antifreeze solution placed in the receiver at the beginning of the season must be taken into account with either method.

3.3.4 Methods of measurement

Two methods are commonly used for measuring the precipitation caught in the gauge: a graduated measuring cylinder and a graduated dip-rod.

A measuring cylinder should be made of clear glass with a low coefficient of expansion and should be clearly marked with the size of gauge for which it is to be used. Its diameter should not be more than about one third of that of the rim of the gauge.

The graduations should be finely engraved. In general, markings should be at 0.2 mm intervals with whole millimetre lines clearly indicated. It is also desirable that the line corresponding to 0.1 mm should be marked. Where it is not necessary to measure rainfall to this accuracy, every 0.2 mm up to 1.0 mm and every millimetre above that should be marked, with every 10-mm line clearly indicated. For accurate measurements, the maximum error of the graduations should not exceed ±0.05 mm at or above the 2-mm graduation mark and ±0.02 mm below this mark.

To achieve this accuracy with small amounts of rainfall, the inside of the measuring cylinder should be tapered at its base. In all measurements, the bottom of the water meniscus should be taken as the defining line. It is important to keep the measure vertical and to avoid parallax errors. It is helpful, in this respect, if the main graduation lines are repeated on the back of the measure.

Dip-rods should be made of cedar or other suitable material that does not absorb water to any appreciable extent, and should have a capillarity effect that is small.

Wooden dip-rods are unsuitable if oil has been added to the collector, and rods of metal or other material from which oil can be readily cleaned must then be used.

They should be fitted with a brass foot to avoid wear and be graduated according to the relative areas of cross-section of the gauge orifice and the receiving can, making allowance for the displacement due to the rod itself. Marks at every 10 mm should be shown. The maximum error in the dip-rod graduation should not exceed ±0.5 mm at any point. Although the measurement may be made with a dip-rod, it should be checked by using a rain measure as well, whenever possible.

It is also possible to measure the catch by weighing. There are several advantages to this procedure. The total weight of the can and contents should be weighed, and the weight of the can should then be subtracted. There is no danger of spilling the contents, and none is left adhering to the can. However, the common methods are simpler and cheaper.

3.3.5 Errors and accuracy of readings

The errors involved in measuring the catch collected in a gauge are small compared with the uncertainty due to the effect of the exposure of the instrument if reasonable care is taken in the readings. Daily gauges should be read to the nearest 0.2 mm and preferably to the nearest 0.1 mm. Weekly or monthly gauges should be read to the nearest 1 mm. The main sources of error likely to arise are the use of inaccurate measures or dip-rods, spilling of some water when transferring it to the measure, and the inability to transfer all the water from the receiver to the measure.

In addition to these errors, losses by evaporation can occur. These are likely to be serious only in hot dry climates, and with gauges visited only at infrequent intervals.

Evaporation losses can be reduced by placing oil in the receiver or by designing the gauge so that only a small water surface is exposed, ventilation is poor, and the internal temperature of the gauge does not become excessive. Also, the receiving surface of the gauge must be smooth, so that the raindrops do not adhere to it. It should never be painted.

In winter where rains are often followed immediately by freezing weather, damage to the receiver, and consequent loss by leakage, can be prevented by the addition of an antifreeze solution. This again mainly applies to gauges visited infrequently.

Allowance for the solution added must, of course, be made when measuring the gauge catch. All gauges should be tested regularly for possible leaks.

3.3.6 Correction of systematic errors

Owing to the effects of wind, wetting, evaporation, blowing snow and splashing, the amount of precipitation measured is usually lower (by 3 to 30 per cent or more) than that which actually fell. This systematic error may be corrected if the readings are to be used for hydrological calculations (WMO, 1982). Before carrying out any corrections, the original measured data should be securely archived. Published data should be clearly labelled "measured" or "corrected", as applicable.

The corrections for these effects are generally based on relationships between the components of the error and the meteorological factors. Thus, the loss from wind field deformation near the gauge rim is related to wind speed and precipitation structure.

The latter can be characterized, depending on the time period used, by the proportion of rainfall at low intensity ($i_p \leq 0.03$ mm min^{-1}), by a logarithm of rainfall intensity, by air temperature and/or humidity, and the type of precipitation. Loss from wetting is related to the number of precipitation events and/or days, while loss from evaporation is a function of the saturation deficit and wind speed. Excess measured precipitation as a result of blowing or drifting snow is related to wind speed.

The above-mentioned meteorological factors may be derived from standard meteorological observations performed at the gauge site or in its vicinity, if daily corrections are to be applied. At sites without such meteorological observations, only estimates for time periods longer than one day, for example, one month, should be used.

The value of the correction varies from 10 to 40 per cent for individual months, depending on the type

Table I.3.1. Main components of the systematic error in precipitation measurement and their meteorological and instrumental factors listed in order of general importance

$$P_k = kP_c = k(P_g + \Delta P_1 + \Delta P_2 + \Delta P_3 \pm \Delta P_4 - \Delta P_5)$$

where P_k is the adjusted precipitation amount, k is the correction factor, P_c is the precipitation caught by the gauge collector, P_g is the measured precipitation in the gauge, and P_1 to P_5 are corrections for components of systematic error as defined below:

Symbol	*Component of error*	*Magnitude*	*Meteorological factors*	*Instrumental factors*
k	Loss due to wind field deformation above the gauge orifice	2–10% 10–50%[a]	Wind speed at the gauge rim during precipitation and the structure of precipitation	The shape, orifice area and depth of both the gauge rim and collector
$\Delta P_1 + \Delta P_2$	Losses from wetting on internal walls of the collector and in the container when it is emptied	2–10%	Frequency, type and amount of precipitation, the drying time of the gauge and the frequency of emptying the container	The same as above and, in addition, the material, colour and age of both the gauge collector and container
ΔP_3	Loss due to evaporation from the container	0–4%	Type of precipitation, saturation deficit and wind speed at the level of the gauge rim during the interval between the end of precipitation and its measurement	The orifice area and the isolation of the container, the colour and, in some cases, the age of the collector, or the type of funnel (rigid or removable)
ΔP_4	Splash-out and splash-in	1–2%	Rainfall intensity and wind speed	The shape and depth of the gauge collector and the kind of gauge installation
ΔP_5	Blowing and drifting snow		Intensity and duration of snow storm, wind speed and the state of snow cover	The shape, orifice area and depth of both the gauge rim and the collector

[a] Snow

of estimate of the meteorological factors employed.

The main components of the systematic error in precipitation measurement are given in Table I.3.1.

The correction factor k for the effect of wind field deformation above the gauge orifice, estimated experimentally for various gauges, is given in Figure I.3.4. It is a function of two variables, the wind speed during precipitation at the level of the gauge rim and the velocity of the falling precipitation particles. The latter depends on the structure of the precipitation.

The absolute value of wetting loss depends on the geometry and material of the gauge collector and container, on the number of measurements of precipitation, and on the amount, frequency and form of precipitation. It is different for liquid, mixed and solid precipitation, and can be estimated by

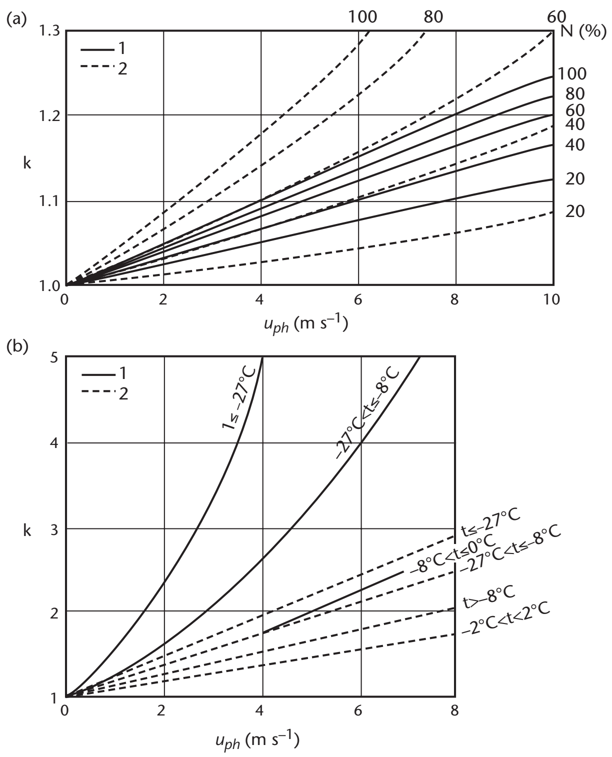


Figure I.3.4. Correction factor k as a function of the wind speed during precipitation at the level of the gauge rim (u_{ph}) and the parameter of the precipitation structure N and t for: (a) liquid precipitation; and (b) mixed and solid precipitation. 1 = Hellman gauge without windshield; 2 = Tretyakov gauge with windshield; t = air temperature during snowstorms; N = fraction in percentage of monthly totals of rain falling with an intensity smaller than 0.03 mm min^{-1} (UNESCO, 1978)

weighing or volumetric measurements in a laboratory. The wetting loss for solid precipitation is generally smaller than for liquid precipitation because the collector is usually wetted only once during snow melt.

The total monthly wetting loss, ΔP_1, can be estimated by using the equation:

$$\Delta P_1 = \overline{a}\, M \tag{3.1}$$

where $\overline{a}$ is the average wetting loss per day for a particular collector and M is the number of days with precipitation.

In cases where the amount of precipitation is measured more than once a day, the total monthly wetting loss is:

$$\Delta P_{1,2} = a_x\, M_p \tag{3.2}$$

where a_x is the average wetting loss per measurement of precipitation for a particular gauge and form of precipitation and M_p is the number of measurements of precipitation during the period concerned.

Evaporation loss can be estimated as follows:

$$\Delta P_3 = i_e\, \tau_e \tag{3.3}$$

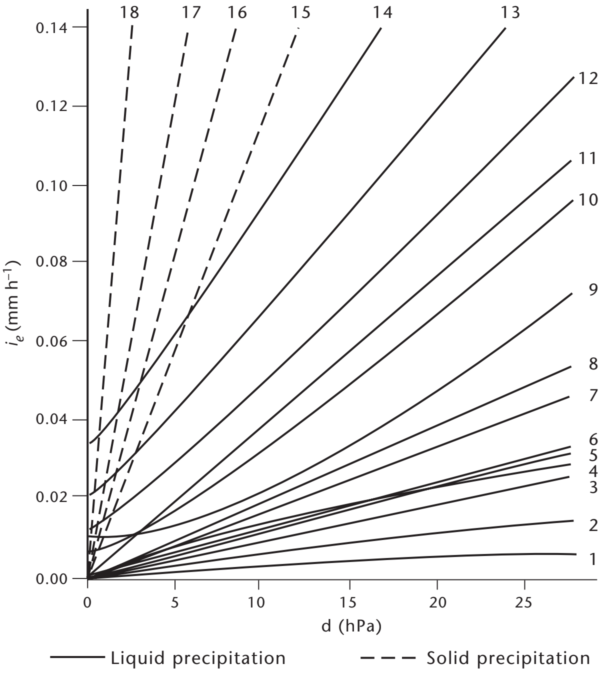
where i_e is the intensity of evaporation and τ_e is the time that elapsed between the end of precipitation and its measurement. The value of i_e depends on the construction, material and colour of the gauge, on the form and amount of precipitation, the saturation deficit of the air d (hPa), and on wind speed at the level of the gauge rim during evaporation. It is difficult to estimate i_e theoretically because of the complex configuration of a precipitation gauge. However, i_e can be computed by using empirical equations or graphical functions as shown in Figure I.3.5. The value of τ_e can be estimated by using precipitation recording gauges, but it also depends on the number of precipitation observations per day. It is three to six hours for liquid precipitation if measured twice per day and six hours for snow because the evaporation takes place during the snowfall.

The net error due to splash-in and splash-out of water can be either negative or positive, and therefore assumed as zero for most types of properly designed precipitation gauges (3.3.2). The error resulting from snow blowing into the gauge should be considered during snowstorms with wind speed larger than 5 m s^{-1}. The half-day values can be estimated at the gauge sites with visual observations of the duration of blowing snow, and in those with known data for wind speed and number of days with both blowing and drifting snow. The long-term monthly averages can be estimated from the graph in Figure I.3.6 if the duration of snowstorms and wind speed are known.

Besides these systematic errors there are random observational and instrumental errors. Their effect can often be neglected because of the high values of the systematic errors.

3.4 RECORDING RAINGAUGES [HOMS C53]

Five types of precipitation recorders are in general use: the weighing type, the float type, the



Note: Intensity of evaporation (i_e) for various gauges: (a) Liquid precipitation: (i) Australian standard gauge 1, 2, 7, 11 for $P \leq 1$ mm; 1.1 to 20 mm; > 20 mm (all for wind speeds, $u_e > 4$ m s^{-1}), and for $u_e \geq 4$ m s^{-1}, respectively; (ii) Snowdon gauge in a pit 3, 6, 8 for $P \leq 1$ mm, 1.1 to 10 mm and ≥ 10 mm, respectively; (iii) Hellmann gauge 4; (iv) Polish standard gauge 5; (v) Hungarian standard gauge 9; (vi) Tretyakov gauge 10, 12, 13, 14 for wind speeds at the level of the gauge rim of 0 to 2, 2 to 4, 4 to 6 and 6 to 8 m s^{-1}, respectively; (b) Solid precipitation: Tretyakov gauge 15, 16, 17, 18 for wind speeds 0 to 2, 2 to 4, 4 to 6 and 6 to 8 m s^{-1}, respectively, where i_e is the intensity of evaporation in mm h^{-1} and τ_e is the time elapsed between the end of the precipitation and the measurement of precipitation.

Figure I.3.5. Evaporation losses from precipitation gauges

tipping-bucket type, distrometers and the acoustic type. The only satisfactory instrument for measuring all kinds of precipitation utilizes the weight or the momentum/optical detection principle. The use of the other types is primarily limited to the measurement of rainfall.

3.4.1 Weighing–recording gauge

In these instruments, the weight of a receiving can plus the precipitation accumulating in it is recorded continuously, either by means of a spring mechanism or with a system of balance weights. Thus, all precipitation is recorded as it falls. This type of gauge normally has no provision for emptying itself, but by a system of levers, it is possible to make the pen traverse the chart any number of times. These gauges have to be designed to prevent excessive evaporation losses, which may be reduced further by the addition of sufficient oil or other evaporation suppressing material to form a film over the water surface. Difficulties caused by oscillation of the balance in strong winds can be reduced by fitting the instrument with an oil damping mechanism. The main utility of this type of instrument is in recording snow, hail and mixtures of snow and rain. It does not require that the solid precipitation be melted before it can be recorded.

3.4.2 Float gauge

In this type of instrument, the rainfall is fed into a float chamber containing a light float. As the level of the water rises, the vertical movement of the float is transmitted by a suitable mechanism into the movement of the pen on the chart. By suitably

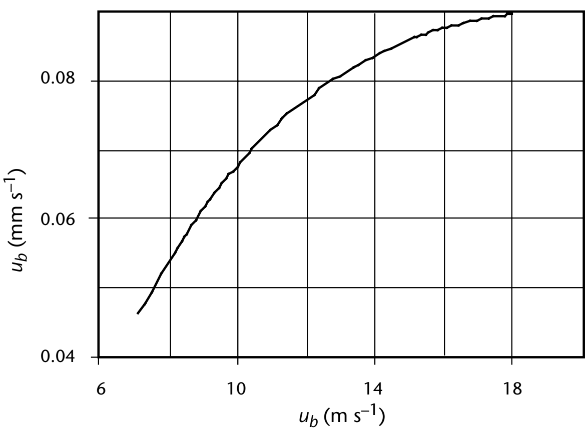


Figure I.3.6. Long-term seasonal intensity of blowing snow (i_b) as a function of long-term wind speed (u_b) at the level of the anemometer (10 to 20 m) during blowing snow

adjusting the dimensions of the receiving funnel and the float chamber, any desired scale on the chart can be obtained.

To provide a record over a useful period (at least 24 hours is normally required), the float chamber has either to be very large (in which case a compressed scale on the chart is obtained), or some automatic means has to be provided for emptying the float chamber quickly whenever it becomes full. The pen then returns to the bottom of the chart. This is usually done with some sort of siphoning arrangement. The siphoning process should start fully at a definite time with no tendency for the water to dribble over, either at the beginning or at the end of the siphoning, which should not take longer than 15 seconds. In some instruments, the float chamber assembly is mounted on knife edges so that the full chamber overbalances. The surge of the water assists in the siphoning process, and when the chamber is empty it returns to its original position. Other rainfall recorders have a forced siphon that operates in less than five seconds. One type has a small chamber separate from the main chamber which accommodates the rain that falls during siphoning. This chamber empties into the main one when siphoning ceases, thus ensuring a correct record of total rainfall.

A heating device should be installed inside the gauge if there is a possibility of freezing. This will prevent damage to the float and float chamber owing to water freezing and will enable rain to be recorded during that period. A small heating element or electric lamp is suitable where a supply of electricity is available, but, if not, other sources of power have to be employed. One convenient method is to use a short length of heating strip wound around the collecting chamber and connected to a large capacity battery. The amount of heat supplied should be kept to the minimum necessary in order to prevent freezing, because the heat will affect the accuracy of the observations by stimulating vertical air movements above the gauge and by increasing evaporation losses.

3.4.3 **Tipping-bucket gauge**

The principle of this type of recording gauge is very simple. A light metal container is divided into two compartments and is balanced in unstable equilibrium about a horizontal axis. In its normal position the container rests against one of two stops, which prevents it from tipping completely. The rain is led from a conventional collecting funnel into the uppermost compartment. After a predetermined amount of rain has fallen, the bucket becomes unstable in its normal position and tips over to its other position of rest. The compartments of the container are so shaped that the water can then flow out of the lower one leaving it empty. Meanwhile, the rain falls into the newly positioned upper compartment. The movement of the bucket, as it tips over, is used to operate a relay contact and produce a record that consists of discontinuous steps. The distance between each step represents the time taken for a pre-specified amount of rain to fall. This amount of rain should not be greater than 0.2 mm if detailed records are required. For many hydrological purposes, in particular for heavy rainfall areas and flood-warning systems, 0.5 to 1.0 mm buckets are satisfactory.

The main advantage of this type of instrument is that it has an electronic pulse output and can be recorded at a distance, or for simultaneous recording of rainfall and river stage on a water stage recorder. Its disadvantages are:

(a) The bucket takes a small but finite time to tip, and during the first half of its motion, the rain is being fed into the compartment already containing the calculated amount of rainfall. This error is appreciable only in heavy rainfall (Parsons, 1941);
(b) With the usual design of the bucket, the exposed water surface is relatively large. Thus, significant evaporation losses can occur in hot regions. This will be most appreciable in light rains;
(c) Because of the discontinuous nature of the record, the instrument is not satisfactory for use in light drizzle or very light rain. The time of beginning and ending of rainfall cannot be determined accurately.

3.4.4 **Rainfall-intensity recorder**

A number of rainfall-intensity recorders have been designed and used for special purposes. However, they are not recommended for general purposes because of their complexity. A satisfactory record of rainfall intensity can usually be determined from a float- or weighing-type recorder by providing the proper timescale.

3.4.5 **Distrometers**

Distrometers measure the spectrum of precipitation particles either through the momentum transferred to a transducer as the hydrometeors hit a detector, or through the image/reflectivity of the hydrometeors illuminated by light or microwaves (Bringi and Chandrasekar, 2001). They have the advantage of providing comprehensive information on hydrometeor size distributions (Figure I.3.7). These devices are available commercially albeit at a high cost compared with tipping-bucket raingauges.

3.4.6 Acoustic type

The measurement of rainfall over lakes and the sea is particularly problematic. However, the noise raindrops make as they hit a water surface may be detected using a sensitive microphone. The noise spectrum reveals the raindrop size distribution, and hence rainfall amount. Such systems are now available commercially. Over land, acoustic profilers, actually designed to measure wind profiles, may also make measurements of rainfall.

3.4.7 Methods of recording the data

Whether the rainfall recorder operates by the rise of a float, the tipping of a bucket or some other method, these movements must be converted into a form that can be stored and analysed later. The simplest method of producing a record is to move a time chart by a spring or an electrically-driven clock, past a pen that moves as the float or weighing device moves. There are two main types of charts: the drum chart, which is secured around a drum that revolves once a day, once a week, or for such other period as desired, and the strip chart, which is driven on rollers past the pen arm. By altering the speed of the strip chart, the recorder can operate for periods of one week to a month or even longer. The timescale on the strip chart can be large enough for intensity to be calculated with ease.

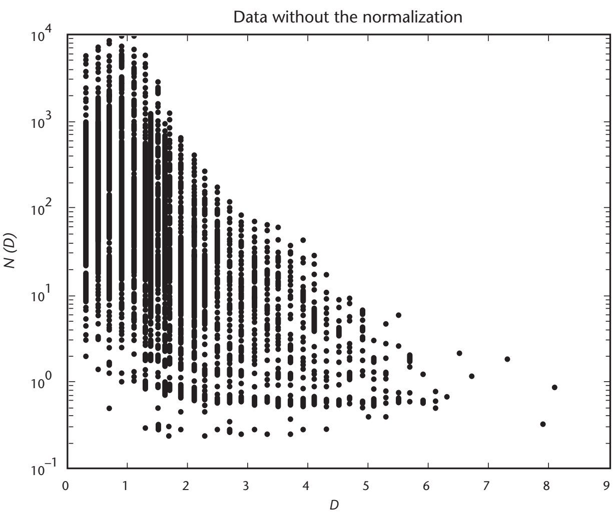


Figure I.3.7. ***N (D)*** **[mm^{-1}m^{-3}] versus *D* [mm] for 70 two-minute average drop size distributions measured by a 2D-video distrometer in convective rain cells in Florida**

The value to be recorded may also be mechanically or electronically converted to digital form and recorded on magnetic media at uniform time intervals for later automatic reading and processing. A wide range of magnetic media and solid state recorders are available.

The movement of a float, bucket, or weighing mechanism can also be converted into an electric signal and transmitted by radio or wire to a distant receiver, where records may be collected from a number of recorders on data-logging equipment (2.5.5).

3.5 SNOWFALL AND HAIL [HOMS C53]

Snow that accumulates in a drainage basin is a natural storage reservoir from which a major part of some basin's water supply is derived. This section describes procedures for the measurement of snow cover. Discussion on snow surveys and on snow cover network design is provided in 2.4.2. Guidance for the use of satellite remote-sensing of snow cover is covered in 3.13. Additional discussion of snow cover measurement is given in *Snow Cover Measurements and Areal Assessment of Precipitation and Soil Moisture* (WMO-No. 749).

3.5.1 Depth of snowfall

Snowfall is the amount of fresh snow deposited over a limited period. Measurements are made of depth and water equivalent. Direct measurements of fresh snow on open ground are made with a graduated ruler or scale. A mean of several vertical measurements should be made in places where there is considered to be an absence of drifting snow. Special precautions should be taken so as not to measure old snow. This can be done by sweeping a suitable patch clear beforehand or covering the top of the snow surface with a piece of suitable material (such as wood, with a slightly rough surface, painted white) and measuring the depth down to this. On a sloping surface (to be avoided if possible), measurements should also be made with the measuring rod in a vertical position. If there is a layer of old snow it would be incorrect to calculate the depth of a snowfall from the difference between two consecutive measurements of the total depth of the fresh and old snow, because of the continuous settling of the old snow. Where strong winds have occurred, a large number of measurements should be made to obtain a representative depth.

The depth of snow may also be measured in a fixed container of uniform cross-section after the snow has been levelled without being compressed. The container should be well above the average snow level, for example, at least 50 cm above the maximum observed level, and not exposed to drifting snow. The receiver should be at least 20 cm in diameter and should either be sufficiently deep to protect the catch from being blown out or else be fitted with a snow cross, that is, two vertical partitions at right angles, subdividing it into quadrants.

Ordinary unshielded receivers are unreliable when the wind is strong because of the wind eddies around the mouth of the receiver. Their catch is usually much less than that of a shielded gauge. However, large errors may be caused, in spite of the use of a shield, by the collection of drifting snow. Such errors can be reduced by mounting the gauges 3 to 6 m above the surface.

3.5.2 Water equivalent of snowfall

The water equivalent of a snowfall is the amount of liquid precipitation contained in that snowfall. It should be determined by one of the methods given below. It is important to take several representative samples:

(a) Weighing or melting – Cylindrical samples of fresh snow are taken with a suitable snow sampler and either weighed (the column of snow is known as a snow pillar) or melted;
(b) Using raingauges – Snow collected in a non-recording raingauge should be melted immediately and measured by means of an ordinary measuring cylinder graduated for rainfall.

The weighing-type recording gauge may also be used to determine the water content of snowfall. During snowfall periods, the funnels of the gauges should be removed so that any precipitation can fall directly into the receiver. Snow pillars are widely used in the western United States, where the SNOw TELemetry (SNOTEL) network uses over 500 gauges. High melt rates can take place under high wind speeds with the passage of a warm front.

3.5.3 Snow cover

3.5.3.1 Snow courses

A snow course is defined as a permanently marked line where snow surveys are taken each year. Snow courses must be carefully selected so that measurements of water equivalents will provide a reliable index of the water in snow storage over the entire basin.

In mountainous areas, the selection of appropriate locations for snow courses may be a challenging exercise because of the difficult terrain and serious wind effects. Criteria for the ideal location of a snow course in mountainous areas are:

(a) At elevations and exposures where there is little or no melting prior to the peak accumulation if the total seasonal accumulation is to be measured;
(b) At sites sufficiently accessible to ensure continuity of surveys;
(c) In forested areas where the sites can be located in open spaces sufficiently large so that snow can fall to the ground without being intercepted by the trees;
(d) At a site having protection from strong wind movement.

Criteria for suitable snow course locations are the same as those for siting precipitation gauges for measurement of snowfall.

In plain areas, the snow course locations should be selected so that their average water equivalents will represent, as nearly as possible, the actual average water equivalent of the area. Thus, it is desirable to have snow courses in typical landscapes, such as in open fields and forests, with different snow accumulation conditions.

If the snow cover in an area under consideration is homogeneous and isotopic and if there exists a spatial correlation function for the depth or water equivalent of the snow, the length of the snow course or the number of measuring points along it needed to determine a mean value to a given accuracy can be determined.

3.5.3.2 Points of measurement

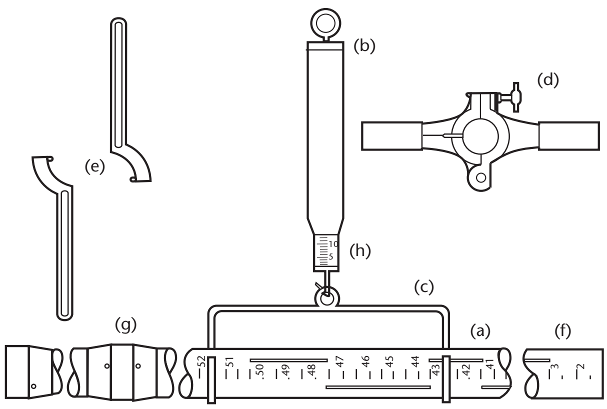
Measurements at a snow course in a mountainous terrain usually consist of samples taken at points spaced 20 to 40 m apart. More samples will be required in large open areas where snow will tend to drift because of wind action. Because sufficient knowledge of the tendency of the snow to drift may be initially lacking, it may be necessary to provide for an extensive survey having long traverses and a large number of measurements. Once the prevailing length and direction of the snowdrifts have been ascertained, it should be possible to reduce the number of measurement points. In plain regions, the distance between points of snow density sampling should be 100 to 500 m. Depth of snow along the snow course should also be measured at about five equally spaced points between the density samples.

Each sampling point should be located by measuring its distance from a reference point marked on a map of the snow course. Stakes should be set high enough to extend above the deepest snow and offset from the course far enough not to affect the snow cover. They may be placed as markers opposite each point where snow samples are to be taken, or at as many points as necessary, to minimize possible error in locating the sampling point. The ground surface should be cleared of rocks, stumps and brush for 2 m in all directions from each sampling point.

Watercourses and irregular ground surfaces should also be avoided by at least 2 m. If a course meanders through timber and if small openings are used as places of sampling, each point should be located with respect to two or three marked trees.

3.5.3.3 Snow-sampling equipment [HOMS C53]

Snow-sampling equipment commonly consists of a metal or plastic tube (sometimes in sections for portability) with a snow cutter fixed at its lower end and with a length scale stamped on its exterior surface throughout its length, a spring or level balance for determining the weight of the snow cores, a wire cradle for supporting the tube while it is being weighed and tools for operating the snow sampler. A typical set of equipment for deep snow, shown in Figure I.3.8, is described in the following way:



(a) snow-sampling tube
(b) tubular spring balance
(c) cradle
(d) driving wrench
(e) spanner wrenches
(f) cutter
(g) screw couplings
(h) scale

Figure I.3.8. Snow-sampling equipment

(a) Cutter – The cutter must be designed to penetrate various types of snow, through crusted and icy layers and, in some cases, through solid ice layers of appreciable thickness that may form near the surface. The cutter must not compact the snow so that an excessive amount of snow is accepted by the interior of the cutter. The cutter must seize the core base with sufficient adhesion to prevent the core from falling out when the sampler is withdrawn from the snow.
Small diameter cutters retain the sample much better than large cutters, but larger samples increase the accuracy in weighing. The shape of the cutter teeth should be designed to allow sufficient back feed on the cutter to remove the ice chips. The cutter should be as thin as practicable but somewhat larger than the outside diameter of the driving tube. This construction allows the chips to find a dumping area when carried backward by the feed on the cutter. The horizontal cutting surface on the cutter blade should be sloped slightly backward to carry the chips away from the interior of the cutter and should be kept sharp so that there is a definite separation of the snow at the inner wall. A large number of teeth provide a smooth cut and keep the cutter free of large chunks of ice;
(b) Sampler tube – In most cases, the inside diameter of the driving tube is larger than the inside diameter of the cutter. The core, therefore, is able to proceed up the tube with a minimum of interference from friction on the wall. However, in normal snow, the core will tend to move over and rub on the walls of the driving tube. Therefore, the walls should be as smooth as possible so that the core may proceed upward without undue friction. In most cases, samplers are constructed of anodized aluminium alloy. While the surface may appear smooth, it cannot be assumed that this will assure non-adhesion of the snow, especially when sampling is made of wet spring snow with a coarse-grained structure. The application of wax may minimize sticking. Some samplers are provided with slots so that the core length may be determined. In general, especially with wet snow, the core length inside may be considerably different from the true depth of the snow measured on the outer markings on the sampler. The slots also provide an entrance for a cleaning tool. The advantage of the slotting arrangement is that errors due to plugging may be immediately detected and erroneous samples may, obviously, be discarded at once. However, the slots may allow extra snow to enter the sampler and increase the measured water equivalent;

(c) Weighing apparatus – The standard way to measure the water equivalent of snow samples is to weigh the snow core collected in the sampler. The core is retained in the sampler, and the sampler and core are weighed. The weight of the sampler is known.

Generally, weighing is accomplished by means of a spring scale or by a special balance. The spring scale is the most practical approach as it may be easily set up and read even under windy conditions. However, the spring scale is accurate only to about 10 g, and the error in weighing by this method may be appreciable for small diameter samplers and shallow depths of snow. Scale balances, potentially more accurate, are very difficult to use in wind. It is doubtful if the intrinsically greater accuracy of this system can be realized except in calm conditions.

Another approach is to store the samples in plastic containers or bags and return them to a base station where they may be accurately weighed or melted and measured with a graduated cylinder. In practice, this procedure is difficult to carry out as the samples must be bagged without loss, carefully labelled, and carried back to the base. The advantage of measurement in the field is that any gross errors due to plugging the sampler, or losses due to part of the sample falling out, may be readily recognized, and repeat readings can be taken at once.

The results may be recorded on site with other pertinent observations and, if a good notebook is used, there can be little chance of confusion as to the location or the sampling conditions.

In all measurements of this type, the extremely difficult physical conditions under which observations must frequently be made should always be kept in mind, and practical consideration should prevail in sampler designs.

3.5.3.4 Snow-sampling procedures

Sampling points should be located by measuring from a reference mark, as indicated on the map of the snow course. Missing a point by more than a few metres may result in significant error.

In order to cut the core, the sampler is forced vertically downward through the snow cover until it reaches the ground. If snow conditions permit, a steady downward thrust, causing an uninterrupted flow of the core into the tube, is best. A minimum amount of turning in a clockwise direction is possible without interrupting the downward thrust. This brings the cutter into play, which is desirable for quick penetration of thin ice layers.

With the cutter at or slightly below ground level and the sampler standing vertically, the reading on the scale that corresponds to the top of the snow is observed.

When the depth that the sampler has penetrated beyond the bottom of the snow cover is ascertained and deducted from this reading, the result is recorded. This is an important reading because it is used in computing the snow density.

In order to prevent loss of core through the cutter while the sampler is withdrawn from the snow, sufficient soil is gathered in the cutter to serve as a plug. The extent to which this will have to be done depends on the condition of the snow.

About 25 mm of solid soil may be required to hold slush. A trace of ground litter on the lower end of the sampler indicates that no loss has occurred.

The length of snow core obtained is observed through the tube slots and read on the scale on the outside of the sampler. After this reading is corrected for any foreign matter picked up in the cutter, it is recorded. The purpose of this reading is to provide a means for judging quickly if a complete sample of the snow cover has been obtained.

The measurement is completed by carefully weighing the snow core in the tube.

The weight of the snow core in equivalent centimetres of water can be read directly on the scale of the balance. The density of the snow is computed by dividing the water equivalent of the snow by the depth of the snow. The density should be reasonably constant over the entire course. A large deviation from the average usually indicates an error in measurement at an individual point.

3.5.3.5 Accuracy of measurements

The accuracy of measurements of snow depth or the water content of snow cover at individual points of the snow course depends on the graduations of the scale being used and on instrumental and subjective errors.

3.5.3.6 Depth and extent of snow cover

Measurements of snow cover over extended areas together with an established local correlation with density make it possible to approximate the water content of the snowpack.

The most common method for determining the depth of snow cover, primarily in regions of deep snow, is by means of calibrated stakes fixed at representative sites that can be inspected easily from a distance. This procedure may be acceptable if the representativeness of the site is proven and if the immediate surroundings of the site (about 10 m in radius) are protected against trespassing. The readings are taken by sighting over the undisturbed snow surface.

The stakes should be painted white to minimize undue melting of snow immediately surrounding them. The entire length of the stake should be graduated in metres and centimetres.

In inaccessible areas, stakes are provided with crossbars so that they can be read from a distance with the aid of field glasses, telescopes, or from aircraft. In the case of measurements of snow depth from aircraft, visual readings of snow stakes may be supplemented by large-scale photographs of the snow stakes, which make the readings less subjective.

The vertical depth of snow cover is also measured by direct observation with a graduated snow tube, usually during the course of obtaining the water equivalent.

3.5.3.7 Radioisotope snow gauges

Radioactive gamma sources are used in various ways to measure water equivalent of snow. Attenuation of gamma radiation may be used to estimate the water equivalent of a snow cover between a source and a detector. One type of installation (vertical) is used to measure total water equivalent above or below a point source. A second installation (horizontal) measures water equivalent between two vertical tubes at selected distances above the ground.

Installation of isotope snow gauges requires relatively expensive and complex instrumentation. In addition, adequate safety measures should be part of any installation, especially where a comparatively high energy source is required. In all cases, consultation with the appropriate licensing or controlling agencies during the development stage is essential and will eliminate many difficulties later on. Although these constraints may limit the use of these gauges, they are a valuable tool and provide the possibility of continuous recording that is particularly useful in inaccessible regions.

Vertical radioisotope snow gauges

Measurement of snow density with the use of radioactive isotopes depends on attenuation of gamma rays traversing a medium. This attenuation is a function of the initial energy of the rays and the density and thickness of the substance traversed. A high energy source of gamma radiation is required, and cobalt-60 is frequently used for this purpose because of its high gamma energy and long half-life (5.25 years).

The source, contained in a lead shield, is placed so that the upper surface of the shield is on the same level as the ground surface, and the beams of gamma rays are directed on the radiation detector above the snow. The detector is a Geiger–Müller or scintillation counter. The impulses from the counter are transmitted to a scalar or, in the case of continuous recording, to an integrator and recorder.

The source of radiation may also be placed in the soil at a certain depth (50–60 cm) so that the gamma rays pass not only through the snow cover but also through a layer of soil. By this means, it is possible to obtain data during the melting of snow pertaining to the quantity of water permeating into the soil or flowing off the surface. There is also a third way of placing the system in the field. The radiation detector counter is placed under the ground surface and the source with shielding is placed above the expected maximum snow layer. This arrangement reduces temperature variations of the detector and provides a constant background count.

Horizontal radioisotope snow gauges

In France and the United States, various modifications of telemetering radioisotope snow gauges have been developed, giving a horizontal and vertical profile of the layer of snow and transmitting the results of measurements to base stations via land, radio or satellite. In both types, the measuring element consists of two vertical tubes of the same length, at a distance of 0.5 to 0.7 m from each other. One tube contains a source of gamma-radiation (Caesium-137 with a half-life of 30 years and activity of 10 or 30 mCi), while the other contains a detector (Geiger–Müller counter or scintillation crystal with photo-multiplier). In the process of obtaining a profile, a special motor, synchronous with the detector, moves the radioactive source upwards and downwards in the tube.

By recording the intensity of the horizontal flux of gamma pulses outside and at various levels inside the layer of snow and by suitably processing the data at a base station, it is possible to determine the depth of snow cover and the density and water content of the snow at a given depth. Furthermore, freshly fallen snow, liquid precipitation and the rate of melting of the snow can be determined.

3.5.3.8 Snow pillows

Snow pillows of various dimensions and materials are used to measure the weight of snow that accumulates. The most common pillows are flat circular 3.7-m diameter containers of rubberized material filled with a non-freezing liquid. The pillow is installed on the surface of the ground, flush with the ground, or buried under a thin layer of soil or sand. In order to prevent damage to the equipment and to preserve the snow cover in its natural condition, it is recommended that the site be fenced. Under normal conditions, snow pillows can be used for 10 years or more.

Hydrostatic pressure inside the pillow is a measure of the weight of the snow on the pillow. Measurement of the hydrostatic pressure is by means of a float-operated water-level recorder or a pressure transducer. Snow pillow measurements differ from those made with standard snow tubes, especially during the snow melt period. They are most reliable when the snow cover does not contain ice layers, which can cause bridging above the pillows. A comparison of the water equivalent of snow, determined by snow pillow, with measurements by the standard method of weighing, showed differences of 5 to 10 per cent.

3.5.3.9 Natural gamma radiation surveys

The method of gamma radiation snow surveying is based on attenuation by snow of gamma radiation emanating from natural radioactive elements in the ground. The greater the water equivalent of the snow, the more the radiation is attenuated. Measurement of gamma radiation can be made by terrestrial or aerial survey. The ratio of gamma radiation intensity measured above the snow cover to that measured over the same course before snow accumulation provides an estimate of the water equivalent.

Aerial gamma surveys of snow cover

While the snow course is a series of point measurements, the aerial survey is an integrated areal estimate of snow cover equivalent. The method is intended for mapping the water equivalent of snow in flat country or in hilly country with a range in elevation up to 400 m. In regions with more than 10 per cent of their areas in marshland, the measurements of water equivalent of snow cover are made only for those areas without marshes, and the integrated characteristics are applied to the area of the entire basin. The usual flying height for an aerial gamma survey is 25 to 100 m above the land surface.

Measurements consist of the total count for a large energy range and spectral counts for specific energy levels. The spectral information permits correction for spurious radiation induced by cosmic rays and radioactivity of the atmosphere. The accuracy of an aerial gamma survey of snow cover depends primarily on the limitations of the radiation measuring equipment (for example, the uniformity of operation of the measuring instruments), fluctuations in the intensity of cosmic radiation and radioactivity in the layer of the atmosphere near the ground, soil moisture variations in the top 15 cm, uniformity of snow distribution and absence of extensive thawing (for example steady flying conditions, or errors in setting course for successive flights). The expected error ranges between ±10 per cent, with a lower limit of approximately 10 mm water equivalent.

Detailed experiments have shown that the standard deviation of measurements of the water equivalent of snow made from an aircraft over a course of 10 to 20 km is about 8 mm and is of a random nature.

To obtain the water equivalent of snow over an area up to 3 000 km^2, with an error not exceeding 10 per cent, recommended lengths of course and distances between courses are given in Table I.3.2.

A great advantage of the gamma survey method is that it yields an aerial estimate of water equivalent over a path along the line of flight. The effective

Table I.3.2. Recommended lengths of flight courses (L) and distance between courses (S)

Natural regions	*S km*	*L km*
Forest-steppe	40–50	25–30
Steppe	40–50	15–20
Forest	60–80	30–35
Tundra	80–100	35–40

width of the path is approximately two to three times the altitude. A second advantage is that the attenuation rate of the gamma rays in snow is determined solely by the water mass independent of its state.

Ground surveys

A hand-carried detector provides a means of measurement of the averaged water equivalent for a band width of approximately 8 m for the length of the course. Water equivalents from 10 to 300 mm may be measured. The accuracy of the measurement ranges from ±2 mm to ±6 mm depending on changes in soil moisture, distribution of the snow, as well as the stability of the instrument system.

A stationary ground-based detector, such as a Geiger–Müller counter or scintillation crystal with photo-multiplier, may also be installed over a snow course area and be used to monitor the water equivalent of an area. However, the occurrence of precipitation carries considerable gamma radiating material to the snow cover, and measurements during and following precipitation are affected by this additional radiation.

Decay of the radiating material permits accurate readings of the water equivalent, approximately four hours after precipitation ceases. Comparison of readings before and after the occurrence of precipitation will provide information on the change in the water equivalent of the snow cover.

3.5.4 Hail pads

Direct measurements of the size distribution of hail are made using, for example, a 1 m x 1 m square of material such as polystyrene on to which hail stones fall leaving an indentation the size of which may be measured.

3.6 RAINFALL ESTIMATION FROM CATCHMENT WATER BALANCE

This chapter is concerned primarily with instrumentation, however, it is important to appreciate that integrated measurements of catchment rainfall can be derived from consideration of the water balance equation in ungauged basins where no instrumentation is available. The amount of water percolating into the soil is related to the effective rainfall, that is, the difference between the rainfall reaching the ground and that evaporated from the surface and vegetation. A simple input-storage-output hydrological model of the catchment may be used to relate the measured river hydrograph to the effective rainfall (Chapter 4).

3.7 OBSERVATION OF PRECIPITATION BY RADAR [HOMS C33]

3.7.1 Uses of radar in hydrology

Radar permits the observation of the location and movement of areas of precipitation, and certain types of radar equipment can yield estimates of rainfall rates over areas within range of the radar (Bringi and Chandrasekar, 2001). For hydrological purposes the effective radar range (European Commission, 2001) is usually 40 to 200 km depending on the radar characteristics, such as antenna beam, power output and receiver sensitivity. The hydrological range of the radar is defined as the maximum range over which the relationship between the radar echo intensity and rainfall intensity remains reasonably valid. The rate of rainfall in any area of precipitation within hydrological range can be determined provided the radar is equipped with a properly calibrated receiver gain control.

Precipitation attenuates the radar beam and this effect is greatest for short wavelength radar. On the other hand, long wavelength radar does not detect light rain and snow as readily as shorter wavelength equipment. The selection of a suitable wavelength depends on climatic conditions and the purposes to be served. All three of the radar bands given in Table I.3.3 are in use for observation of precipitation.

3.7.2 The radar–rainfall equation

The radar equation is sometimes referred to as the free space maximum range equation (FSMR). This equation defines the maximum range that can be anticipated from a particular radar system. For precipitation targets, where rainfall is considered

Table I.3.3. Weather radar frequency bands

Band	*Frequency (MHz)*	*Wavelength (m)*
S	1 500–5 200	0.1930–0.0577
C	3 900–6 200	0.0769–0.0484
X	5 200–10 900	0.0577–0.0275

to have filled the radar beam, the equation has the form:

$$P_r = P_t \pi^3 G^2 \theta.\phi.h K^2 Z / 512(2 \ln 2) R^2 \lambda^2 \quad (3.4)$$

where P_r is the average power in watts received from a series of reflected pulses, P_t is the peak power transmitted in watts, G is the antenna gain, θ and ϕ are the horizontal and vertical beam widths, h is the pulse length in metres, R is the range in metres, λ is the wavelength in metres, K^2 is the refractive index term of rain (0.9313 for 10-cm radar equipment assuming a temperature of 10°C), and Z is the reflectivity.

It should be understood that equation (3.4) is only applicable under certain assumptions (European Commission, 2001; Meischner, 2003), and therefore is likely to be in error when these conditions are not met. Nevertheless, it is the basis of all radar estimates of precipitation from a single frequency radar.

The rainfall rate in mm h^{-1} is related to the median drop diameter, as follows:

$$\sum d^6 = aP_i^b \quad (3.5)$$

where P_i is the rainfall intensity in mm h^{-1} and a and b are constants. Many determinations have been made of the drop size distribution measured at the ground and the conversion by means of the fall speeds of different sized drops to a particular rainfall rate. The most common equation in use is:

$$Z = 200 P_i^{1.6} \quad (3.6)$$

3.7.3 Factors affecting measurements

A summary of the factors affecting measurements is discussed in turn below.

3.7.3.1 Wavelength

The use of S-band frequency, as in the United States, removes problems associated with attenuation of the radar beam as it passes through precipitation. The use of C-band frequency in much of the rest of the world improves sensitivity, but does result in attenuation problems. C-band systems are presently a factor of about two cheaper than S-band systems for the same aerial dimensions, although this may change with the introduction of tuneable travelling wave tube (TWT) technology in the future. Correction procedures have been developed for attenuation at C-band (3.7.3.4).

3.7.3.2 Ground clutter

Both the main part of the radar beam and the side lobes may encounter ground targets. This will cause strong persistent echoes, known as ground clutter, to occur, which may be misinterpreted as rainfall. Although radars may be sited to minimize these echoes, it is not possible to remove them altogether, and other techniques such as the use of Doppler processing with clutter map removal (Germann and Joss, 2003) must be used.

In addition to producing permanent echoes, interception of the beam by the ground also causes occultation or screening of the main part of the beam. In this case only a fraction of the power illuminates the rain at longer ranges. This may be corrected provided at least 40 per cent of the beam is unobstructed. It is possible to simulate the visibility from a radar site using a digital terrain model, although the result is not perfect owing to small errors in the pointing angle, uncertainties in the simulation of the refraction of the radar beam and insufficient resolution of the digital terrain model particularly at close range.

3.7.3.3 Beam width and range

At 160 km, the radar beam may be several kilometres wide, depending on the beam width employed. Normally, there will be marked variations in the radar reflectivity within this large sampling volume. Thus, an average value over a large volume is obtained, rather than a point value. The radar equation is based on the beam being filled with meteorological targets. Therefore, one would not expect the values of rainfall rate obtained with a radar to be highly correlated with point raingauge measurements. However, the areal pattern displayed by radar should generally be much more representative of the true storm isohyetal configuration than that measured by most raingauge networks.

In showery conditions it has been found that the frequency of echoes recorded at 160 km was only about 4 per cent of that of echoes recorded at 64 km. Therefore, a shower which fills the beam at 64 km would only fill about one eighth of the beam at 160 km. This result is due to a combination of beam width and beam elevation factors.

3.7.3.4 Atmospheric and radome attenuation

Microwaves are attenuated by atmospheric gases, clouds and precipitation. The attenuation experienced by radio waves is a result of two effects: absorption and scattering. In general, gases act only as absorbers, but cloud and raindrops both scatter and absorb. For radar sets operating at the longer wavelengths, attenuation is not a problem and can usually be neglected. The generally accepted form of expressing attenuation is in decibels. The decibel (dB) is used as a measure of relative power and is expressed as:

$$dB = 10 \log_{10} P_t / P_r \qquad (3.7)$$

where P_t and P_r would be the power transmitted and power received. Signal attenuation as related to rate of rainfall and wavelength is given in Table I.3.4.

Corrections may be made to account for the distance from the radar site ($1/R^2$, R = range), for the attenuation due to beam dispersion by atmospheric gases (0.08 dB km^{-1} one way) and for signal attenuation through heavy rain (Table I.3.4). However, such procedures (Meischner, 2003; Collier, 1996) may be unstable in cases of severe attenuation and operational corrections are "capped" (limited) at an upper limit based on what is reasonable. In the future it may be that procedures based on the use of multiparameter radar (3.7.8) will be employed.

Table I.3.4. Radar signal attenuation due to precipitation (dB km^{-1})

Rate of rainfall ($mm\ h^{-1}$)	*Wavelength (m)*			
	0.1	0.057	0.032	0.009
1.0	0.0003	0.002	0.007	0.22
5.0	0.0015	0.015	0.061	1.1
10.0	0.003	0.033	0.151	2.2
50.0	0.015	0.215	1.25	11.0
100.0	0.015	0.481	3.08	22.0

Distance (km) over which precipitation at a given rate of rainfall must extend to give an attenuation of 10 dB at various wavelengths

Rate of rainfall ($mm\ h^{-1}$)	*Wavelength (m)*			
	0.1	0.057	0.032	0.009
1.0	33 000	4 500	1 350	45
5.0	6 600	690	164	9.1
10.0	3 300	310	66	4.5
50.0	600	47	8	0.9
100.0	300	21	3.2	0.4

3.7.3.5 Refraction of beam and multiple scattering

Radar waves are propagated through space with a refractive effect which gives the waves a curved path. The approximate mean radius is four thirds the mean radius of the Earth. As a result of vertical moisture discontinuities, additional refractive bending of the radar beam can occur. This produces what is often called ducting or trapping of the radar beam and either causes the radar beam to re-curve earthward or to be curved upwards overshooting precipitation 80 to 120 km away. The meteorological conditions favouring ducting (trapping) can be determined mathematically.

If the radar pulses are scattered by water-coated ice spheres, then a process known as three-body scattering may produce unusual precipitation signatures. The "hail spike" is such a signature. This process involves the combined scattering from the ground as well as from hydrometeors, but is not a common phenomenon.

3.7.3.6 Vertical velocity

Vertical velocity of rainfall in very intense convective systems may cause radar echoes, which in turn may cause the relationship between rainfall, R, and radar reflectivity, Z, to differ quite significantly from that in still air. For example, in a downdraft of 8 m s^{-1} the reflectivity value for a given rainfall rate would be about 3 dB less than in still air, producing an underestimate of the rainfall rate by 40 per cent.

3.7.3.7 Vertical profile of reflectivity

The main factor introducing bias into radar estimates of surface precipitation is the vertical measurement geometry of weather radars. At increasing range a radar measurement volume is located at increasing altitude above the Earth's surface. Hence a radar measurement of reflectivity aloft can be accurate, but not representative of conditions at the surface. This is not a measurement error, but a sampling problem.

When the radar beam intersects the level at which snow starts to melt the reflectivity is enhanced, and the result is known as the bright band. This occurs a few hundred metres below the freezing level (see Figure I.3.9). In this figure, when snow is present throughout the depth of the precipitation, the bright band is not present and the radar reflectivity decreases with increasing height.

The vertical profile of reflectivity (VPR) above each point on the Earth's surface can be denoted as $Z_e(h)$, where h is the height above the surface at range r from the radar site. The shape of VPR determines the magnitude of the sampling difference (Koistinen and others, 2003). Denoting the shape of the radar beam pattern f^2 then,

$$Z_e\,(h, r) = \int f^2\,(y)\, Z_e\,(h)\, dy \qquad (3.8)$$

The integration is performed vertically (y) from the lower to the upper edge of the beam. The vertical sampling difference (in decibels, or dB) is then

$$c = 10 \log\,(Z_e\,(0) / Z_e\,(h, r)) \qquad (3.9)$$

where $Z_e\,(0)$ is the reflectivity at the surface in VPR. Hence by adding the sampling difference c to the measured reflectivity aloft (dBZ), the reflectivity at the surface $dBZ(0, r)$ is,

$$dBZ\,(0, r) = dBZ + c \qquad (3.10)$$

In snowfall the sampling difference increases as a function of range, indicating a significant under-estimation of the surface precipitation even at close ranges. However, in rainfall the radar measurement is relatively accurate up to a range of 130–140 km. When the height of the bright band is more than about 1 km above the radar antenna, the overestimation due to it will compensate for the underestimation effect of snow in the beam. Hence, a radar measurement is more accurate at longer ranges than it would be without the bright band.

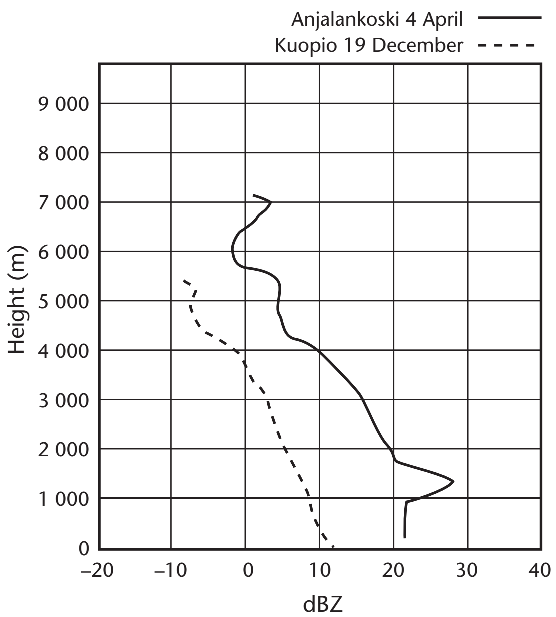


Figure I.3.9. Two vertical profiles of reflectivity averaged from single polar volumes at ranges of 2–40 km from the radar. The solid line represents rain and the dashed line snowfall
(from Koistinen and others, 2003)

In some parts of the world there exists orographic growth of precipitation at low levels over hills exposed to strong moist maritime airflows. This growth may be reflected in VPR, but sometimes may occur below the height of the radar beam. In this case, to some extent the growth may be estimated by applying climatological correction factors. In some synoptic situations, for example ahead of warm fronts, the opposite effect may be observed, mainly low level evaporation. In this situation it is more difficult to apply a correction, and it may be necessary to use the output from a mesoscale numerical forecast model. However, care should be taken in using model output to do this and it may be more reliable to use as low a radar beam elevation as possible to observe the evaporation in VPR.

3.7.4 **Snow and hail**

A radar is capable of measuring snowfall as accurately as rainfall. However, the accuracy depends very much upon VPR and, in particular the height of the bright band. As for rainfall the a and b (equation 3.5) in the $R{:}Z$ relationship may vary greatly depending upon, for example, whether the snow is wet or dry. Typical values often used are a = 2000 and b = 2.0.

When a radar observes hail, the backscattered power is no longer proportional to the sixth power of the particle size, and Mie theory is applicable. When only hail is observed in the pulse volume the number of hail in the pulse volume is directly related to the hail diameter D_H (mm) by (Auer, 1972):

$$N\,(D_H) = 561\, D_H^{-3.4} \qquad (3.11)$$

Hence assuming Rayleigh scattering in the hail at C-band:

$$Z = 10 \log_{10}\,(561\, D_H^{2.6})\ dBZ \qquad (3.12)$$

Problems occur in heavy rainfall which often contains hail. This increases the reflectivity. Whilst polarization radars are capable of detecting the presence of hail directly, single polarization radars are not, and other techniques must be used (Collier, 1996).

3.7.5 Scanning strategy

Automatic electronic radar digitizers, capable of sampling radar echoes at the rate of 80 range-increments for each 1–2° of azimuth, have been developed and are now standard on all commercial radars. Their data are recorded on magnetic tape or other magnetic media for immediate on-site computer analysis, transmission via data link to a remote computer, or for retention and later analysis. The results of this type of sampling are similar to those for manual methods, except that the number of discrete samples is larger by at least one order of magnitude than the finest grid overlay. The time required to sample and record the entire radar sweep is about 1 to 4 minutes and 8 to 14 elevations may be used.

The actual scan strategy deployed is dependent upon the use to which the radar data are to be put. Two types of scanning strategies, known as contiguous and interlaced, may be employed. For contiguous scanning the radar beam is scanned rapidly through all elevations after which the procedure is repeated. For interlaced scanning every other beam elevation is missed out in the first scan sequence, and the elevations omitted are implemented during the second scan sequence immediately following the first. The data from individual radar beams may be combined to use the best data at each particular bin based on beam height, terrain effects and beam blockage.

3.7.6 Summary of accuracy considerations

As discussed previously, a number of difficulties must be faced in retrieving estimates of surface rainfall from radar. Of particular importance is the vertical variability of radar reflectivity (VPR; see also 3.7.3.7).

Vignal and others (2000) discuss three approaches to the determination of VPR. They found that a correction scheme based on a climatological profile improves the accuracy of daily radar rainfall estimates significantly within 130 km of the radar site. The fractional standard deviation (FSE) is reduced from the uncorrected value of 44 per cent to a corrected value of 31 per cent. Further improvement is achieved using a single, mean hourly average VPR (FSE = 25 per cent) and a locally identified profile (FSE = 23 per cent). This analysis was carried out for both stratiform and convective rainfall, although better improvement is obtained for stratiform events.

Although it has now been recognized that the application of a VPR correction is an essential first step after the removal of ground clutter echoes in estimating surface precipitation, bias errors may remain. The appropriateness of subsequent raingauge adjustment (Meischner, 2003) to mitigate residual errors remains uncertain. However, the application of time-integrated raingauge data does produce improvements, particularly in mountainous terrain (Collier, 1996).

It seems clear that a single polarization radar can be used to measure daily rainfall to an accuracy approaching 10 per cent, provided VPR is adjusted carefully. Such a level of accuracy is similar to that provided by raingauges. However, sub-daily rainfall is much more problematic, particularly at C-band and shorter wavelengths for which attenuation is a serious problem in convective rainfall. Hourly rainfall over catchments of about 100 km^2 may be measured to a mean accuracy of 20 per cent in stratiform rain, but only 40 per cent or so in heavy convective rain. The current aim for point measurements of instantaneous rainfall is within a factor of two although this has not yet been achieved reliably.

3.7.7 Doppler radar

3.7.7.1 Basics

To measure the absolute speed of movement (or velocity) of a raindrop and its direction of movement instantaneously, it is necessary to use a radar with a very precise transmitter frequency and a receiver system sensitive to the changes of frequency induced by a moving target, even though in the case of meteorological targets these changes may be small. This type of radar is sometimes referred to as a coherent radar but more frequently as a Doppler radar because it uses the well-known Doppler effect. A more detailed discussion of this topic along with added references is found in publications by the European Commission (2001) and Meischner (2003).

Doppler radars have been used for research purposes for many years, both singly and, more recently, in multiple networks consisting usually of two or three radars. They have played a considerable part in the investigation of the atmosphere and are considered by some radar meteorologists to be indispensable in the study of the dynamics of air masses, particularly of convective clouds. However, problems of interpretation of data still exist, and it is only in recent years that serious consideration has been given to their use in operational systems. In certain parts of the world, particularly those subject to violent weather, they constitute operational systems and are now regarded as a highly desirable form of radar. They are inherently more complex though not more expensive than conventional radars, and they require greater processing power and more maintenance effort. Despite this, radars with Doppler capability exist in large national network in the United States and elsewhere. Doppler radars can be used for general forecasting purposes to provide data that may reveal signatures useful for the advanced warning of such phenomena as tornadoes and severe storms. Moreover, they can provide more information on the intensity and structure of these phenomena than any other practical means.

3.7.7.2 Clutter cancellation

Most systems measure precipitation intensities in a conventional way as well as providing Doppler data. One important advantage is that it is possible to determine with some degree of accuracy the position and extent of permanent, and to some degree anomalous propagation, echoes, which are, by definition, stationary from the Doppler channel. This information can then be used in an attempt to ensure that only precipitation data are measured by the non-Doppler channel. As with any other system of clutter removal, the method is unlikely to be totally successful alone since, under some transmission and weather conditions, permanent echoes can appear to move and, conversely, precipitation is sometimes effectively stationary. Doppler clutter cancellation is usually accompanied by other procedures for removing clutter such as clutter maps and use of VPR.

To obtain echoes from refractive inhomogeneities and for the purpose of measuring precipitation intensity to the greatest possible ranges compared with conventional non-Doppler radar or for studying the structure of severe storms, longer wavelengths are necessary, preferably 10 cm.

3.7.7.3 Measuring winds

A number of different techniques for estimating winds using a single Doppler radar have been developed (Bringi and Chandrasekar, 2001; European Commission, 2001; Meischner, 2003). Commercial radar manufacturers now offer some of these techniques, and they are used to produce both mean profiles of horizontal wind velocity and radial winds under certain assumptions. These data are not yet in operational use to help in the estimation of precipitation, although this may change in the near future as such data begin to be assimilated routinely into numerical weather prediction (NWP) models (3.17).

3.7.8 Multi-parameter radar

Development of multi-parameter radar hardware with which to measure the properties of hydrometeors has been slow since the initial production of high-speed switches enabling the rapid alternate transmission of horizontally and vertically polarized microwave radiation. However, in recent years following work on other polarization states such as circular, and the recognition of the potential of multi-parameter radar for measuring precipitation, attention to the design of the hardware has increased.

Versatile research radars such as the CSU-CHILL installation in the United States and Chilbolton in the United Kingdom have provided the test beds from which to consider what polarization base is most effective in measuring rainfall and hydrometeor type. It is now possible to make simultaneous transmissions of horizontal (H) and vertical (V) radiation without the need for a high-power polarization switch. This form of simultaneous transmission is now being implemented on the National Severe Storms Laboratory's (NSSL) research WSR-88D S-band radar, and is being considered as the basis of the polarimetric upgrades to the operational WSR-88D radars in the United States.

3.8 GROUND-BASED RADAR AND RAINFALL MONITORING TECHNIQUES

Ground-based weather radars have been used operationally for more than 20 years in some countries, mostly in combination with raingauge networks, which are often used to calibrate them. Rainfall estimates made by weather radars are sometimes more useful than those made by raingauges because they are continuous in time and space and provide areal coverage (D'Souza and others, 1990). However, associated with them are problems dealing with backscatter, attenuation, absorption and reflection, particularly in areas of varying relief and signal calibration. Although the weather radar networks operated in European and North American countries by the national meteorological agencies adequately service the primary meteorological requirement of daily weather reporting and forecasting, the need for quantitative estimates of rainfall to support applications in hydrology and water resources, especially flood forecasting, has not been so well serviced. Radar is in widespread use as an informal means of initial alert of impending flooding utilizing the moving images of storm systems that it provides. However, quantitative use of radar data is much less common and is constrained by accuracy limitations, especially in mountainous areas and at times when bright band effects are apparent (WMO, 1998). Although the informal use of radar for flood warning is widespread, only two or three countries make quantitative use of the data as part of a flow forecasting system. Even then, the radar is used in a complementary way with additional information being provided by networks of raingauges. The development of distributed flood forecasting models (specially tailored to utilize the radar grid data through a model grid formulation) are still at a pre-operational stage. Furthermore, real-time implementation should only be contemplated following detailed offline assessment and proven improved performance relative to simpler and more conventional lumped models (WMO, 1998, 1999). Weather radar data are less immediately suited to applications for design rainfall estimation, compared with their use for flood forecasting, because of the shortness of radar records relative to the storm periods to be inferred. However, this is in part compensated for by the complete spatial coverage that radars provide. Furthermore, the advantages of the high temporal and spatial resolution of radar data ought to be of particular importance for short duration design estimates.

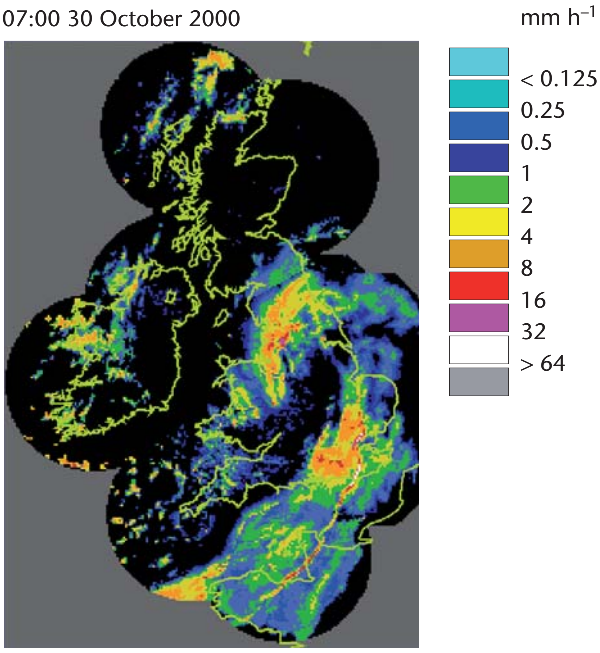


Figure I.3.10. United Kingdom radar network image comprising radar data from the United Kingdom and Ireland at 0700 UTC on 30 October 2000. The different colours represent different rainfall rates in mm h^{-1} as shown. The coastline is shown.
(Courtesy Met Office, United Kingdom)

3.9 OPERATIONAL RADAR NETWORKS

Operational radar networks now exist in many countries. In the United States S-band Doppler radars are used, whereas in Europe C-band systems form most of the networks. An example of a radar network image from the United Kingdom is shown in Figure I.3.10. The boundaries between individual radars are designated by consideration of the heights of the radar beams, presence of ground clutter, areas where the best accuracy is required, etc. The importance of regular maintenance and calibration of radars cannot be overestimated, even though radar technology has now become very reliable, with downtime in some countries being only a few per cent per month, usually planned to occur in no-rain situations.

3.10 DUAL FREQUENCY MICROWAVE LINK ATTENUATION MEASUREMENTS OF RAINFALL

It has been shown (Holt and others, 2000) that good estimates of path-averaged rainfall may be obtained from the difference in signal attenuation caused by rainfall at two frequencies along a microwave communications link. The specific attenuation K (dB km^{-1}) along the link is estimated according to:

$$K = c\,R^{d} \tag{3.13}$$

This relationship depends critically upon the signal frequency, and the parameters c and d which are unknown, but sensitive to temperature, rain drop shape and drop-size distribution. However, if a dual frequency link is used two frequencies and polarization states may be selected for which the specific attenuation differences are relatively insensitive to these unknown parameters. After the raw attenuation measurements have been adjusted for gaseous absorption, there is a linear relationship between this parameter and rainfall rate. An example of the success of this technique in measuring line integrated rainfall is shown in Figure I.3.11.

The installation of a dual frequency microwave link along a radial from a weather radar offers the opportunity to measure the integrated rainfall along the

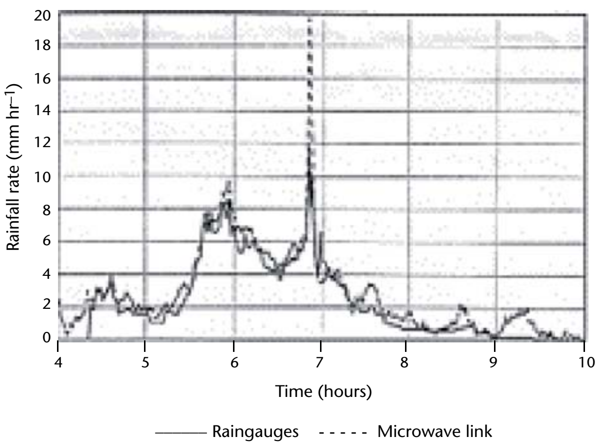


Figure I.3.11. Time series of path-integrated rainfall estimates from raingauges (solid line) and dual frequency microwave link (dashed line) attenuation measurements over north-west England on 10 February 2000
(Holt and others, 2000)

link which may be compared with the same quantity measured by the radar. If the radar operates at an attenuating frequency, then this comparison provides a method of measuring attenuation through rain, or from rain on the radar radome albeit in only one azimuthal direction. This technique is not operational at present.

3.11 OBSERVATIONS OF RAINFALL BY SATELLITE

3.11.1 Basics

Rainfall estimation from space is based on measuring the amount of radiation that is reflected and emitted through cloud tops. Most of the radiation does not penetrate deep into cloud regions containing particles with similar or greater size than the radiation wavelength. Therefore, except for the longest wavelengths, most of the radiation comes from the upper regions of precipitating clouds and can therefore only indirectly be related to surface rainfall. Consequently there are very many techniques using a range of procedures.

3.11.2 Visible and infra-red

Rain intensities vary with the rate of expansion of cold (T < 235°K) cloud top areas. It is assumed that the expansion of the cloud top is an indicator for the divergence aloft and, hence, to the rate of rising air and precipitation. However, when used over a large area, this method does not show significant improvement with respect to the simplest possible method which assumes that all clouds with tops colder than a given threshold temperature T precipitate at a fixed rate G mm h^{-1}, where T = 235°K and G = 3 mm h^{-1} is typical of the eastern equatorial Atlantic. This method was developed into the Global Precipitation Index (GPI), which has been used extensively.

Such area methods work well only for a time-space domain that is large enough to include a large number of storms that provide a good representation of the full evolution of convective rain-cloud systems (for example, 2.5° x 2.5° x 12 hours). Classification of clouds into convective and straiform by the texture of the cloud top temperature has shown some improvement for tropical rainfall over land. However, it fails (along with the rest of the infra-red methods) in mid-latitude winter systems, because there the "convective" relation between cold cloud top area and surface rainfall does not apply to largely non-convective cloud systems.

The use of visible wavelengths to characterize the strength of convection works well when used with infra-red wavelengths to indicate the height of the cloud. However, such procedures can be misleading by the presence of bright cirrus cloud, or the presence of low-level orographic rain.

The atmospheric window of about 10 microns is split into two closely spaced wavebands, centred at 10.8 and 12 microns. Clouds have large absorption and emissivity in the longer waveband. Therefore, the 10.8 micron radiation in thin clouds will be contributed from lower and warmer levels as compared with the 12 micron waveband, creating a brightness temperature difference between the two channels. It has been shown that cirrus clouds can be distinguished from thicker cloud by having larger brightness temperature difference. This helps in eliminating thin clouds from consideration as precipitating cloud.

Very cold cloud top temperature is not always a requirement for precipitation, in which case the infra-red threshold technique breaks down. The precipitation formation processes require the existence of large cloud droplets and/or ice particles in the cloud, which often spread to the cloud top. These large particles absorb the 1.6 and 3.7 micron radiation much more strongly than small cloud droplets. This effect makes it possible to calculate the effective radius (r_{eff} = integral volume divided by integral surface area) of the particles. It has been shown that r_{eff} = 14 microns can serve to delineate precipitating clouds, regardless of their top temperature (Figure I.3.12).

3.11.3 **Passive microwave**

Microwaves provide the measurements that are physically best related to the actual precipitation, especially in the longest wavebands. The interactions of passive microwave with precipitation clouds and the surface are illustrated in Figure I.3.13, using two wavebands, shorter (85 GHz) and longer (19 GHz). Measurement techniques are based on the two physical principles of absorption and scattering.

Absorption-based measurements

Water drops have relatively large absorption/emission coefficient, increasing for the higher frequencies. The emission is proportional to the vertically integrated cloud and rainwater in the low frequencies, but due to the increased emissivity for the higher frequencies the emission saturates for light rain intensities.

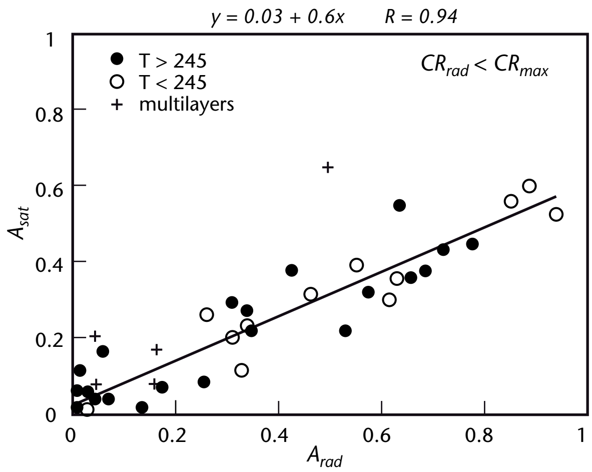


Figure I.3.12. Fraction of precipitating area, defined by the area with $r_{eff} \geq 14$ microns (A_{sat}), as a function of the fraction of precipitating area detected by radar (A_{rad}) for convective clouds. Windows with multi-layered clouds are marked with crosses, windows with cloud-top temperatures higher than 245 K are marked with solid circles, and windows with cloud-top temperatures lower than 245 K are marked with hollow circles. CR_{sat} is the cloud radius parameter and CR_{max} is the maximum cloud radius for a given depth.
(Rosenfeld and Gutman, 1994; Lensky and Rosenfeld, 1997)

Scattering-based measurements

Ice particles have relatively small absorption/emission, but they are good scatterers of the microwave radiation, especially at higher frequencies. Therefore, at high frequencies (85 GHz), the large scattering from the ice in the upper portions of the clouds makes the ice an effective insulator, because it reflects back down most of the radiation emitted from the surface and from the rain. The remaining radiation that reaches the microwave sensor is interpreted as a colder brightness temperature. A major source of uncertainty for the scattering-based retrievals is the lack of a consistent relationship between the frozen hydrometeors aloft and the rainfall reaching the surface.

The two physical principles of absorption and scattering described above have been used to formulate a large number of rain estimation methods. In general, passive microwave rainfall estimates over the ocean were of useful accuracy. However, over the equatorial Pacific, passive microwave does not show significantly improved skill when compared with the simplest infra-red method (GPI).

Over land the passive microwave algorithms can detect rain mainly by the ice scattering mechanism, and this indirect rain estimation method is less accurate. Moreover, rainfall over land from clouds which do not contain significant amounts of ice aloft, goes mostly undetected.

3.11.4 **Active microwave (rain radar; Tropical Rainfall Measurement Mission)**

A major limiting factor in the accuracy of passive microwave methods is the large footprint, which causes partial beam filling, especially at the higher frequencies. The resolution is greatly improved with the Tropical Rainfall Measurement Mission (TRMM) satellite, with a corresponding improvement in the expected accuracy of the microwave rain estimates. The TRMM satellite has a radar transmitting at a wavelength of 2.2 cm (active microwave) and microwave radiometers (19 to 90 GHz) (Figure I.3.14). The resolutions of these instruments range from about 1 km for the visible and infra-red radiometer, about 10 km for the microwave radiometers and 250 m for the radar. The radar has provided an improvement in the accuracy of instantaneous rain estimates over those previously achieved from space. Since TRMM samples each area between 35 degrees north and south, at best, twice daily, the sampling error is the dominant source of inaccuracy.

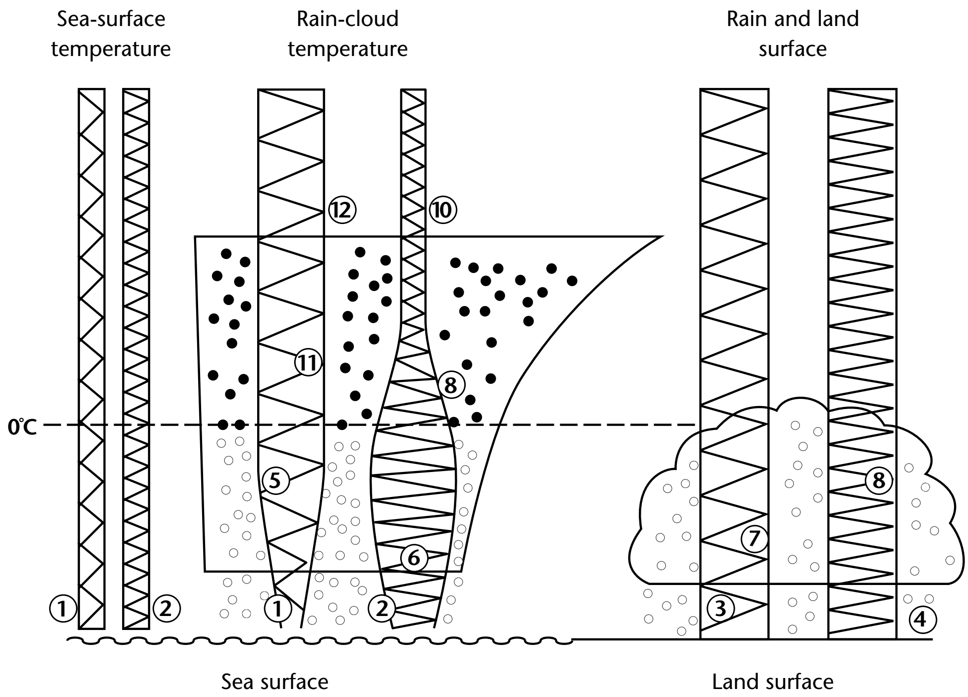


Figure I.3.13. The interaction of high (for example 85 GHz) and low (for example 19 GHz) frequency passive microwave with precipitation clouds and the surface. The width of the vertical columns represents the intensity of temperature of the upwelling radiation. The illustrated features and their demarcations are: (a) the small emissivity of sea surface for both low (1) and high (2) frequencies; (b) the large emissivity of land surface for both low (3) and high (4) frequencies: (c) the emission from cloud and rain drops, which increases with vertically integrated liquid water for the low frequency (5), but saturates quickly for the high frequency (6); (d) the signal of the water emissivity at the low frequency is masked by the land surface emissivity (7); (e) the saturated high frequency emission from the rain (8) is not distinctly different from the land surface background (4); (f) ice precipitation particles aloft backscatter down the high-frequency emission (9), causing cold brightness temperatures (10), regardless of surface emission properties; (g) the ice lets the low frequency emission upwell unimpeded (11), allowing its detection above cloud top as warm brightness temperature (12).
(Rosenfeld and Collier, 1999)

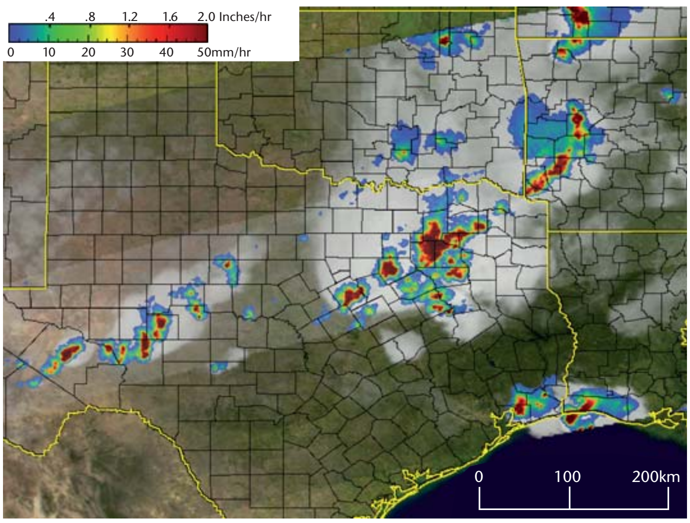


Figure I.3.14. Heavy rainfall over Texas derived from the TRMM Microwave Imager and Precipitation Radar on the TRMM satellite at 0439 UTC 1 May 2004 (Courtesy NASA)

A combination of the measurements from TRMM-like and geostationary satellites provides the best potential for accurate global precipitation estimates from space. Currently plans are being developed to implement such systems under the general title of the Global Precipitation Mission (GPM).

3.11.5 Summary of accuracy considerations

In tropical regions there can be a significant diurnal cycle in rainfall activity, and the phase and intensity of the cycle may vary from region to region. The low inclination orbit used for TRMM will process in such a way as to sample a full diurnal range of Equator crossing times over the course of a month. This is not the case for satellites in polar orbit for which the Equator crossing time is always the same. The diurnal cycle may therefore increase the errors due to sampling.

For monthly averages over a 280 km^2 and a sampling interval of 10 hours, appropriate for the TRMM satellite, the sampling error is about 10 per cent. However, for convective systems in other regions, which have shorter decorrelation times than observed for tropical rain, the sampling error is likely to be larger.

The validation of satellite algorithms for estimating rainfall accumulations is complex and must be undertaken in ways that ensure that different techniques provide data with similar characteristics, that is, integration times and coverage.

The best accuracy for areal rainfall measurements from space at present is obtained over the tropical oceans, where GPI performs as well as passive microwave techniques for long period (in the order of several months) integrated rainfall. However, errors for individual events may be large because "warm rain" from shallow clouds is common in some places in the tropics. The passive microwave techniques become increasingly advantageous towards higher latitudes where convective rainfall occurs less frequently. Here the best accuracy is achieved by combining passive microwave with infra-red from geostationary satellites. Somewhat lower accuracies of infra-red techniques are achievable in convective rain over land, due to large dynamic and microphysical diversity of rain-cloud systems. This causes a larger variability between the rainfall and the properties of the upper portions of the clouds. The skill of passive microwave techniques is also reduced over land, because its emissivity reduces greatly the usefulness of frequencies lower than 35 GHz. Nevertheless, results over land at 88.5 GHz are encouraging.

3.12 REMOTE-SENSING MEASUREMENTS OF SNOW

Remote-sensing of snow can be accomplished using gamma rays, visible and near IR, thermal IR and microwaves. An overview of the relative sensor band responses to various snowpack properties shows that the microwave band has the greatest overall potential followed by the visible and near-infra-red band. The gamma ray portion is extremely limited by the fact that the sensing must be carried out with low altitude aircraft, and to a lesser extent that it is really only sensitive to a finite snow-water equivalent. Thermal infra-red is also limited in potential, but it can be used from space in night-time situations (Rango, 1993; WMO, 1999). Different approaches for determining snow area, water equivalent and snow properties have been developed. These have been driven for the most part by the availability of data from existing satellites or from experimental aircraft and truck programmes. Remote-sensing data are currently being used operationally in snow cover and snow-water equivalent assessments, and seasonal snow melt runoff forecasts. The potential of satellites to provide usable information on snowpack dynamics is now widely recognized and today many schemes exist that employ satellite-derived snow measurements for snow melt runoff prediction (Lucas and Harrison, 1990).

Even more important than snow extent and location for various snowpack processes is the vertical dimension of the snowpack. This vertical dimension essentially provides the information needed for estimating snow volume which relates directly to the potential for snow melt runoff.

Although the airborne gamma-ray spectrometry approach is a very accurate remote-sensing method for measuring the snow-water equivalent, its previously mentioned drawbacks limit its use. However, airborne gamma-ray data and weather satellite data together provide good possibilities for operational snow cover mapping (Kuittinen, 1989; Carroll, 1990).

Airborne gamma-ray spectrometry can be used to determine the snow-water equivalent values, because snow attenuates the terrestrial gamma radiation (WMO, 1992*b*). Background gamma radiation of the soil is obtained before snowfalls, and subsequent flights are flown to measure the gamma radiation through the attenuating snow cover. The degree of attenuation is related to the snow-water equivalent through various calibration graphs.

As resolutions of passive microwave sensors improve (a Russian microwave radiometer at about 0.8 cm wavelength with approximately 8-km resolution was launched in 1996), all-weather capability will increasingly be exploited. The final advantage of the microwave spectrum is that night-time measurements are easily made because of the reliance on emitted microwave radiation as opposed to reflected visible microwave radiation. Emittance and backscattering of microwave radiation are affected by almost all snow parameters, which complicates the measurement of the most needed parameters: water equivalent, areal extent and amount of free water.

Good relationships have been established between snow depth and microwave emission and backscatter for snowpacks that are dry and uniform with little evidence of layering. Such relationships are not so clear once the snowpack has been subjected to thaw and refreeze cycles, whilst the presence of unfrozen water anywhere in the snowpack results in marked changes in microwave response. In general, the use of microwave radiometry appears more reliable than radar for this type of measurement (Blyth, 1993).

The new Special Sensor Microwave/Imager (SSM/I) data are being used operationally to produce snow-water equivalent maps of the Canadian prairies, which are now supplied operationally to Canadian users (Goodison and Walker, 1993).

The active microwave region has a potential similar to the passive microwave region. However, it should be noted that not only are active microwave observations of the snowpack very sparse and almost non-existent, but the analysis of active microwave data is more complex than that of passive data because of the confusion caused by the effect of surface characteristics (including soils) and geometry considerations on the reflected radar wave. The higher resolution (10 m from space) of the active microwave is a considerable advantage over passive microwave. The major problem is the lack of sensors at about 0.8-cm wavelength for experiments on any kind of platform. Although satellite Synthetic Aperture Radar (SAR) can provide high-resolution data, current single-frequency systems such as ERS-1 are likely to be limited to the recognition of the onset of melt and the delineation of wet snow extent. Some of these problems may be overcome by using multifrequency and multipolarization SAR measurements.

Some of the more promising research on remote sensing measurements of snowfall is included in the list of references at the end of this chapter.

3.13 SATELLITE REMOTE-SENSING OF SNOW COVER

Remote-sensing data are currently being used operationally in snow cover and snow-water equivalent assessments, and seasonal snow melt runoff forecasts. The potential of satellites to provide usable information on snowpack dynamics is now widely recognized, and today many schemes exist that employ satellite-derived snow measurements for snow-runoff prediction.

Only satellites enable seasonal snow cover to be monitored periodically, efficiently and on a sufficiently large scale. Significant remote-sensing data for operational snow mapping are available from satellites such as Satellites pour l'observation de la terre (SPOT), Landsat, National Oceanic and Atmospheric Administration (NOAA), Geostationary Operational Environmental Satellite (GOES), Earth Observation Satellites (EOS) and Defense Meteorological Satellite Program (DMSP). The choice of satellite for snow mapping depends upon the smallest partial area of the region to be monitored. While the accuracy of the snowpack delineation and snow area estimation depends upon the spatial resolution of the sensors involved, operational snow mapping schemes are rarely necessary for such small areas (Lucas and Harrison, 1990). As a result, the Landsat Thematic Mapper (TM) sensor is usually applied in the context of research projects and in some cases, aerial photographs may be preferred to TM imagery as these can be collected for selected cloud-free days and for similar sized areas.

The areal extent of the snow cover is mapped operationally in many countries using weather satellite data. Although snow cover can be detected and monitored with a variety of remote sensing devices, the greatest application has been found in the visible and the near-infra-red region of the electromagnetic spectrum (EMS). The reason is that "the reflectance of snow in the visible and near-infra-red parts of the EMS is much greater than that of any other natural material on the ground and thus snow can easily be detected and the extent of snow cover determined. The reflectivity (albedo) depends upon snow properties such as the grain size and shape, water content, surface roughness, depth and presence of impurities. In particular, the visible red band (0.6–0.7 m) of the multispectral scanner (MSS) on the Landsat has been used extensively for snow cover mapping because of its strong contrast with snow-free areas. It is to be noted that although Landsat and SPOT may provide adequate spatial resolution for snow mapping, their inadequate frequency of coverage hinders their snow mapping capabilities. As a result, many users have turned to the NOAA polar-orbiting satellites with the Advanced Very High Resolution Radiometer (AVHRR); although characterized with a much higher frequency of coverage (every 12 hours as opposed to every 16 to 18 days), the problem with the NOAA-AVHRR data is that the resolution of 1 km (in the visible red band (0.58–0.68 m)) may be insufficient for snow mapping on small basins.

The current EOS AM and PM satellites carry the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument which provides daily data at fairly high spatial resolutions. The EOS programme is also backed up with a series of rather robust snow algorithms. Despite the spatial and temporal resolution problems associated with visible aircraft and satellite imagery, they have proven to be very useful for monitoring both the build-up of snow cover and the disappearance of snow-covered areas in the spring. Meteor (which has been used to delineate snow/no snow lines for river basins and other areas in the then Union of Soviet Socialist Republics) and NOAA data were combined to map snow cover area in basins ranging from 530 to more than 12 000 km^2 (Shcheglova and Chemov, 1982). Although snow can be detected in the near-infra-red band, the contrast between a snow and a no-snow area is considerably lower than with the visible region of EMS. However, the contrast between clouds and snow is greater in the Landsat TM Band 5 (1.57–1.78 m). Thus the near-infra-red band, when available, serves as a useful discriminator between clouds and snow. Visible/near-infra-red difference data from NOAA-9 imagery of the United Kingdom has been used to locate areas of complete or partial snow cover and identify melt and accumulation zones. Daily snow area maps were produced and were subsequently composited to generate weekly estimates of snow distribution. This technique is currently being considered for operational use in the United Kingdom and elsewhere.

Thermal infra-red data has limited importance for snow mapping and measuring properties because it is hindered by cloud cover, and the surface temperature of snow is not always that much different from the surface temperatures of other adjacent areas with different cover, such as rock or grass. However, thermal infra-red data can be useful to help identify snow/no snow boundaries, and for discriminating between clouds and snow with AVHRR data because the near-infrared band has not been available on this sensor. Furthermore, Kuittinen (WMO, 1992*b*) stated that the best result in snowline mapping can be achieved by combining the information of the thermal emission and the reflectance in the visible part of EMS.

Although there are currently many problems with using microwave sensing for mapping snow cover, one major advantage of the microwave approach is the ability to penetrate cloud cover and map snow extent. Owing to its cloud penetration or all weather capability, the microwave wavelength at about 1 cm has the greatest overall potential for snow mapping. However, the current major drawback is the poor passive microwave resolutions from space (about 25 km) so that only very large areas of snow cover can be detected. Large-scale snow cover extent maps are currently produced using geophysical algorithms on the data from satellite microwave radiometers such as Special Sensor Microwave Imager (DMSP) SSM/I. These maps are most reliable over large flat regions with little or low-lying vegetation when snow is dry. The resolution problem can potentially be solved with the use of high-resolution active microwave sensors. Unfortunately, few, if any, experiments with the short wavelength region of the microwave spectrum (about 1 cm wavelength) that is sensitive to snow have been reported.

3.14 OPERATIONAL SATELLITES

Remote-sensing techniques from space provide the capability of observing precipitation and snow cover in real- or near-real-time over large areas, and thus complement the conventional more accurate point measurements or weather radar. Useful data can be derived from satellites used primarily for meteorological purposes, including polar-orbiting NOAA and DMSP and the geostationary GOES, Geostationary Meteorological Satellite (GMS) and Meteosat (Engman and Gurney, 1991).

Operational polar-orbiting satellites also carry sounders such as the TIROS-N operational vertical sounder (TOVS) and the advanced microwave sounding unit (AMSU), which provide data for numerical weather prediction models used for forecasting rainfall. The NOAA series carrying these instruments has now been replaced by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) METOP satellites. While passive microwave radiometers have been operational to date, following the success of the TRMM satellite, there are now well advanced plans to launch a series of satellites carrying visible, IR, passive microwave and active microwave instruments (EPS).

Whereas the ERS-1 and -2 satellites provided semi-operational satellite data, the EUMETSAT ENVISAT satellite has now replaced the ERS satellite and is now in operation providing a range of sensors including SAR. This satellite is complemented by the Japanese Advanced Earth Observation Satellite (ADEOS) system. Meteosat Second Generation (MSG) is also now operational providing high resolution in space and time visible and IR imagery. Multispectral data are also available from LANDSAT, SPOT and, most recently, MODIS.

3.15 DEW

Although the deposition of dew, essentially a nocturnal phenomenon, is not spectacular as a source of moisture, being relatively small in amount and varying locally, it could be of significant interest in arid zones, where it could even be of the same order of magnitude as rainfall. As the process by which moisture is deposited on objects largely depends on the source of moisture, it is necessary to distinguish between dew formed as a result of downfall transport of atmospheric moisture condensed on cooled surfaces, known as dewfall, and that formed by water vapour evaporated from the soil and plants and condensed on cooled surfaces, known as distillation dew. Both sources generally contribute simultaneously to observed dew, although at times they operate separately.

A further source of moisture results from fog or cloud droplets collected by leaves and twigs and reaching the ground by dripping or stem flow. There has been a great tendency to overestimate the average dew over an area, and this is due primarily to overlooking the physical limits on possible quantities of dew. Examination of the energy–budget equation reveals that the latent heat of dewfall and/or distillation dew is unlikely to exceed net radiation and should be less if sensible and soil-heat transfers are taken into consideration. Under favourable conditions there is a definite limit, at the rate of about 1.1 mm h^{-1} for the average rate of dew over an area. However, dew may be substantially increased in local areas where mean temperatures are not horizontally homogeneous and there is small-scale advection from relatively warmer and moister areas to cooler areas. Moreover, the one dimensional form of energy-flux computations should be modified when applied to isolated plants because the pattern of radiation and moisture flux is quite different from that of a homogeneous source. This does not mean that the average deposit over a large horizontal area is affected, but only that some parts gain at the expense of others.

Actual deposition rates will generally fall well below the upper limit.

Much effort has been devoted, but without much success, to devising a means of measuring leaf wetness from artificial surfaces in the hope of yielding results comparable to those for natural conditions. A review of the instrumentation designed for measuring duration of leaf wetness and an assessment of the extent to which various instruments give readings representative of plant surface wetness is given in the Appendix to the *The Influence of Weather Conditions on the Occurrence of Apple Scab* (WMO-No. 140). Any of these devices can only be used as a qualitative guide in any particular situation, or as a crude means of regional comparison. Careful interpretation is required in either role. Unless the collecting surface of these gauges is more or less flush with the surface and of very similar properties, it will not correctly indicate the amount of dew that the natural surface receives.

Theoretically, the flux technique should give reasonable average values over an area, but lack of knowledge of transfer coefficients under very stable conditions makes it extremely difficult to implement. The only certain method of measuring net dewfall by itself is by a sensitive lysimeter. However, this method does not record distillation dew, since no change in weight accompanies distillation dew.

The only generally accepted means of measuring total amount of dew is by the blotting technique, that is, by weighing a number of filter papers both before and after being thoroughly pressed against leaves. A brief outline of dew measurement methods is given in the *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8).

3.16 SAMPLING FOR PRECIPITATION QUALITY

In recent years it has become increasingly apparent that deposition of atmospheric pollutants is of major ecological significance. Most notable have been the effects resulting from acidic precipitation in the United Kingdom, Scandinavia, eastern Canada and the north-eastern United States. For a complete picture of the atmospheric transport of toxic substances, both the wet and dry precipitation must be sampled and analysed as well as the air itself. This section discusses the criteria necessary for the collection of liquid and frozen precipitation samples and of surface deposition. For the analysis of atmospheric deposition over periods of tens to hundreds of years, several other substrates have been found useful in providing a record. These include naturally growing mosses, which quantitatively retain some metals, ice cores from glaciers and bottom sediments. Sampling for precipitation quality is further discussed in 7.2.3.

3.16.1 Rain and snow collectors [HOMS C53]

Many types of collectors have been used to sample precipitation, from a plastic, stainless steel or glass container placed on location at the beginning of a precipitation event, to a sophisticated sequential sampler designed to collect precipitation samples automatically at selected intervals during an event.

A common device for the collection of both wet and dry deposition separately is the double bucket collector. One bucket is used to collect precipitation, while the other bucket collects the dry deposition. The collector is equipped with an automatic sensing system that detects precipitation, liquid or frozen. At the onset of a precipitation event, a cover is moved from the wet bucket to the dry bucket. On cessation of the event, the cover automatically returns over the wet bucket. The sample container normally used is a black polyethylene vessel. It consists of two parts. The top part is a removable rim that has been specially fabricated to ensure a sharply defined uniform area of collection. The second part is the bucket itself. Both the rim and the bucket must be rinsed with distilled, de-ionized water each time a sample is removed. When sampling precipitation for organic contaminants, a stainless steel or glass bucket must be used.

When directional information is desired, associated meteorological instruments can be utilized. Equipment has been designed in which precipitation is directed to one of a number of bottles, depending on the direction of the wind, by means of a wind vane.

Modern snow collectors are similar to rain collectors, except that they are heated to thaw and store the entrapped snow as liquid in a compartment beneath the sampler (HOMS C53).

3.16.2 Dry deposition collection

Many of the problems associated with snow collection also apply to the collection of dry deposition. The double-bucket collector provides a measure of the amount, but considerable controversy exists about the relevance of such a measurements. The air turbulence around such a device is not the same as at the surface of a lake, for example, which leads to differences both in absolute collection efficiency and relative efficiency between different particle sizes. Other methods, such as glass plates coated with sticky materials and shallow pans with liquids, aqueous ethylene glycol or mineral oil, have been suggested.

3.17 ASSIMILATION OF RAINFALL INTO HYDROLOGICAL AND HYDRAULIC MODELS: COMBINING AND ASSESSING DATA FROM DIFFERENT SOURCES

Increasingly work is being undertaken to assimilate measurements of radar reflectivity and surface rainfall into numerial weather prediction models. However, there are a number of inherent difficulties, such as the fact that models deal with features in the weather at scales much larger than the observational data scale and that radar reflectivity is not a direct model diagnostic. Work to use the radar data as a proxy for humidity information has met with some success (Meischner, 2003), but the problem is far from solved. It is likely that advanced three- and four-dimensional variational assimilation techniques (3D-VAR, 4D-VAR) will be needed.

The input of rainfall data to hydrological models also presents difficulties. Quality control of the radar or satellite-based inputs is essential. Also, it is necessary to employ advanced statistical techniques to ensure that the error characteristics of the input data are represented in model output flows. The hydrograph produced using such input must never be used without some accompanying measure of uncertainty.

3.18 GLOBAL PRECIPITATION CLIMATOLOGY PROJECT

The Global Precipitation Climatology Project (GPCP) has provided, since 1979, monthly global rainfall estimates over areas of 2.5° latitude x 2.5° longitude grids (Adler and others, 2003). Independent rainfall estimates, usually based upon raingauge observations, provide essential assessment of the accuracy of the GPCP rainfall estimates, although sampling errors between these systems of measurement require statistical evaluation. This was achieved recently by the decomposition of the variance of the satellite and raingauge difference into the error of the satellite sensor and the raingauge sampling error (Gebremichael and others, 2003).

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CHAPTER 4

EVAPORATION, EVAPOTRANSPIRATION AND SOIL MOISTURE

4.1 EVAPORATION, EVAPOTRANSPIRATION AND INTERCEPTION

4.1.1 General

Evaporation and transpiration are the primary abstractions of the hydrological cycle. These abstractions are small during a runoff event and can be neglected. The bulk of evaporation and transpiration takes place during the time between runoff events, which is usually long. Hence, these abstractions are the most important during this time interval. The combined effect of evaporation and transpiration is called evapotranspiration. Over large land areas in temperate zones, about two thirds of the annual precipitation is evapotranspired and the remaining one third runs off in streams and through the groundwater to the oceans. In arid regions, evapotranspiration may be even more significant, returning up to 90 per cent or more of the annual precipitation to the atmosphere. Evaporation also links hydrology to atmospheric science and, through transpiration, to agricultural sciences.

4.1.2 Definitions

Evaporation

The process by which water is changed from the liquid or solid state into the gaseous state through the transfer of heat energy is known as evaporation.

In the hydrological cycle evaporation is an important process, so much so that on a continental basis, approximately 70 to 75 per cent of the total annual precipitation is returned to the atmosphere by evaporation and transpiration. In hot climates, the loss of water by evaporation from rivers, canals and open-water storage equipment is a vital matter as evaporation takes a significant proportion of all water supplies. It is significant in the sense that most of the water withdrawn for beneficial uses ultimately returns to streams and aquifers and becomes available for reuse, while the loss of water due to evaporation is entirely lost from the usable supply. Even in humid areas, evaporation loss is significant although the cumulative precipitation tends to mask it so that it is ordinarily not recognized except during rainless periods.

Storage reservoirs expose wide surfaces to evaporation and thus are a major source of water loss even though they may lessen natural evaporation by confining floods in deep storages instead of spreading over wide flood plains.

The factors controlling evaporation have been known for a long time, but evaluating them is difficult because of their interdependent effects. However, in general, evaporation is affected by temperature, wind, atmospheric pressure, humidity, water quality, water depth, soil type and nature, and shape of surface.

Transpiration

Transpiration is defined as a natural plant physiological process whereby water is taken from the soil moisture storage by roots and passes through the plant structure and is evaporated from cells in the leaf called stomata.

The amount of water held in storage by a plant is less than 1 per cent of that lost by it during the growing season. From the hydrological standpoint, therefore, plants are like pumps that remove water from the ground and raise it to the atmosphere.

It is difficult to make precise estimates of the water transpired because of the many variables responsible for the process. Available estimates should be used with due caution taking into consideration the conditions under which these estimates were obtained. Adequate relationships between climatic factors and transpiration are prerequisites if the data derived in one climatic region are supposed to have general utility.

Transpiration is affected by physiological and environmental factors. Stomata tend to open and close in response to environmental conditions such as light and dark, and heat and cold. Environmental factors that affect transpiration are essentially the same as for evaporation, but can be considered a bit differently. For practical purposes, vapour pressure gradient, temperature, solar radiation, wind and available soil moisture are the most important factors affecting transpiration.

Evapotranspiration

The term evapotranspiration (ET) is defined as the water vapour produced from the watershed as a result of the growth of plants in the watershed.

Evapotranspiration and consumptive use include both the transpiration by vegetation and evaporation from free surfaces, soil, snow, ice and vegetation. Here it will be important to give the difference between evapotranspiration and consumptive use. Consumptive use differs from evapotranspiration only in that it includes the water used to make plant tissues (Singh, 1994). In computing evapotranspiration both transpiration and soil evaporation are included. The actual evapotranspiration can be determined by the analysis of the concurrent record of rainfall and runoff from a watershed.

There is an important difference between evapotranspiration and free surface evaporation. Transpiration is associated with plant growth and hence evapotranspiration occurs only when the plant is growing, resulting thereby in diurnal and seasonal variations. Transpiration thus superimposes these variations on the normal annual free water-surface evaporation.

Potential evapotranspiration

The potential evapotranspiration (PET) is defined as the evapotranspiration that would result when there is always an adequate water supply available to a fully vegetated surface.

This term implies an ideal water supply to the plants. In case water supply to the plant is less than PET, the deficient would be drawn from the soil-moisture storage until about 50 per cent of the available supply is utilized. With further moisture deficiency, the actual evapotranspiration (AET) will become less than PET until the wilting point is reached, and when the evapotranspiration stops.

Interception

Interception is that portion of the precipitation that, while falling on the Earth's surface, may be stored or collected by vegetal cover and subsequently evaporated. The volume of water thus lost is called interception loss.

In studies of major storm events and floods the interception loss is generally neglected. However, it may be a very significant factor in water balance studies. Precipitation falling on vegetation may be retained on leaves or blades of grass, flow down the stem of plants and become stem flow or fall off the leaves to become part of the throughfall. The amount of water intercepted is a function of (a) the storm character, (b) the species, age and density of plants and trees and (c) the season of the year. Usually about 10 to 20 per cent of the precipitation falling during the growing season is intercepted and returned to the hydrological cycle through evaporation. Under very dense forest conditions, it may be even as high as 25 per cent of the total precipitation. In temperate regions, evaporation of water intercepted by the vegetation represents an important part of the evapotranspiration. There is a wide variety of techniques used to measure rain interception (water stored in the canopy), canopy-interception-storage capacity, time of leaf wetness, throughfall, canopy evapotranspiration, and interception evaporation (often, but less appropriately, called interception loss). Reviews of interception measurement and leaf wetness methods are given by, for example, Bouten and others (1991) and Lundberg (1993), whereas canopy-storage-capacity measurements are summarized by Klaassen and others (1998). Micrometeorological evaporation methods are described by, for example, Garratt (1984) and Sharma (1985).

4.1.3 **Measurement of evaporation** [HOMS C46]

For a general reference on measurement instruments, see the *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8).

4.1.3.1 Direct methods

Reasonably accurate methods of measurement of evaporation and evapotranspiration are available from pans and small bodies of water and soil, but direct measurement of evaporation or evapotranspiration from large water or land surfaces is not possible at present. However, several indirect methods have been developed that give acceptable results. Evaporation pans and lysimeters are used in networks for this purpose, and are discussed in this chapter. For existing reservoirs and plots or small catchments, estimates can be made by water-budget, energy-budget, and aerodynamic approaches and other available methods. These latter techniques are discussed in this chapter only from the point of view of instruments and observational requirements. Computation of evaporation and evapotranspiration from water and land surfaces by the various indirect methods is also discussed separately in this chapter. Some of the direct methods are as follows.

Pan evaporation

For estimation of evaporation from open water bodies, evaporation records of pans are generally used. The pans could be either square or circular section, mounted entirely above the ground or sunk in the ground so that the water level is approximately that of the ground. They may be mounted on anchored floating platforms on lakes or other water bodies.

Three types of pans deserve special mention: the United States Class A pan (Figure I.4.1), the GGI-3000 pan (Figure I.4.2) and the 20-m^2 tank of the Russian Federation. The United States Class A pan has been recommended by WMO and the International Association of Hydrological Sciences as a reference instrument as its performance has been studied under a range of climatic conditions within wide limits of latitude and elevation. The GGI-3000 pan and 20-m^2 tank are used in the Russian Federation and some other countries with different climatic conditions, as they possess reliable operational qualities and an extremely stable relationship with the meteorological elements that influence evaporation. WMO sponsored comparative observations (WMO, 1976) of the Class A pan, the GGI-3000 pan and the 20-m^2 tank in several countries, which eventually led to some operational recommendations on the suitability of these pans in diverse climatic and physiographic conditions.

In addition to the pan, a number of other instruments, such as integrating anemographs or anemometers, non-recording precipitation gauges, thermometers or thermographs for pan water temperature, maximum and minimum thermometers or thermographs for air temperature or hygro-thermographs or psychrometers, are also needed.

When installing evaporation pans it is important to ensure that the site of the pan is reasonably level and free of obstruction. At sites where normal climate and soil do not permit the maintenance of a soil cover, the ground cover should be maintained as near as possible to the natural cover common in the area. Obstructions such as trees, buildings, shrubs or instrument shelters should not be closer than four times the height of the object above the pan. Under no circumstance should the pan or instrument shelter be placed on a concrete slab or pedestal, or over asphalt or gravel.

The instruments should be located on the evaporation station plot so as to prevent them from casting shadows over the pan. The minimum size of the plot should be 15 m x 20 m. The plot should be fenced to protect the instruments and to prevent animals from drinking the water. The fence should be constructed so that it does not affect the wind structure over the pan. At unoccupied sites, particularly in arid and tropical regions, it is often necessary to protect the pans from birds and small animals by using chemical repellants and a wire mesh. To estimate the error introduced by the wire-mesh screen on the wind field and thermal characteristics of the pan, readings from the protected pan should be compared with those of a standard pan at the nearest comparable occupied site.

The water level in the pan must be measured accurately before and after water is added.

This may be done in two ways:

(a) The water level may be determined by means of a hook gauge consisting of a movable scale and vernier fitted with a hook enclosed in a still-water chamber in the pan. An alternative arrangement is to use a float. A calibrated container is used to add or remove water at

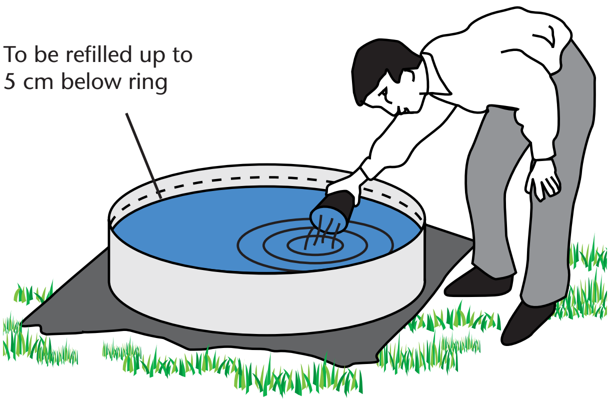

Figure I.4.1. United States Class A pan

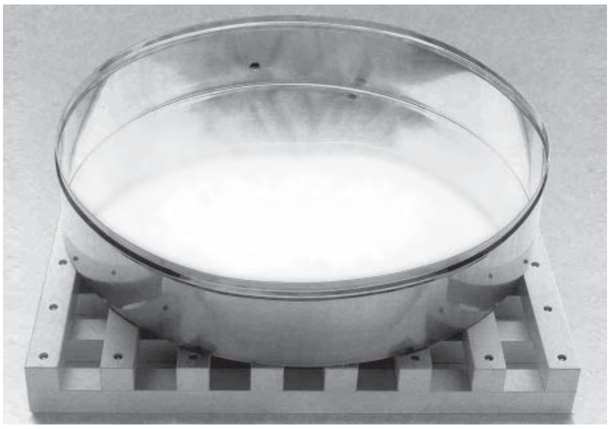

Figure I.4.2. GGI-3000 pan

each observation so as to maintain the water level to a pre-specified point;

(b) The water level may be determined by the following procedure:
   (i) A vessel of small diameter fitted with a valve is placed on top of a benchmark below the water surface in the pan;
   (ii) The valve is opened and the water level in the vessel is allowed to equalize with the water level in the pan;
   (iii) The valve is closed and the volume of water in the vessel is determined accurately in a measuring tube.

The height of the water level above the benchmark is determined from the volume of water in the vessel and the dimensions of the vessel.

Daily evaporation is computed as the difference in water level in the pan on successive days, corrected for any precipitation during the period. The amount of evaporation that has occurred between two observations of water level in the pan is determined by:

$$E = P \pm \Delta d \tag{4.1}$$

where P is the depth of precipitation during the period between the two measurements, and Δd is the depth of water added (+) to or removed (–) from the pan.

Several types of automatic evaporation pans are in use. The water level in the pan is kept automatically constant by releasing water into the pan from a storage tank or by removing water from the pan in the case of precipitation. The amount of water added to or removed from the pan is recorded.

The major difficulty in using a Class A pan for the direct measurement of evaporation arises because of the use of coefficients to convert the measurements from a small tank to large bodies of open water. Fuzzy logic as suggested by Keskin and others (2004) can provide an alternative to the classical evaporation estimation.

Snow evaporation

Evaporimeters made of polyethylene or colourless plastic are used in many countries for measuring evaporation from, or condensation on, snow cover. Snow evaporimeters should have an area of at least 200 cm^2 and a depth of 10 cm. A sample of snow is cut to fill the evaporimeter, the total weight is measured and the evaporimeter is set flush with the snow surface. Care should be taken that surface characteristics of the sample in the evaporimeter are similar to those of the snow cover in which it is placed. At the end of the measurement period, the evaporimeter is removed from the snow cover, the outside is wiped dry and a second measurement of weight is made. The difference between initial and final weights is converted to evaporation or condensation in centimetres. Measurements during periods of snowfall or blowing snow are not valid. During melt, the evaporimeters should be weighed and new samples should be cut at more frequent intervals as the snow cover will be settling, exposing the edge of the evaporimeter and altering air flow over the sample.

4.1.3.2 Indirect methods

Because of problems encountered in making direct measurements of evaporation from lakes and reservoirs, a number of indirect methods, such as the water-budget, the energy-budget, the aerodynamic approach or combination of these, are frequently used. The meteorological elements incorporated into these methods are solar and long-wave radiation, air and water-surface temperatures, atmospheric humidity or vapour pressure, and wind. Instruments and observational procedures for measuring these elements are described in the following subsections. The manner in which observations of the above elements are used in various indirect methods for estimating evaporation is described below in this chapter.

Solar radiation

Incident total solar (short-wave) radiation should be measured at a site near the reservoir with a pyranometer, and the output should be recorded continuously. Incoming short-wave radiation on a horizontal surface is measured with a pyranometer. Most modern types of pyranometers are based on multi-junction thermopiles and are covered by single or double glass domes that allow only radiation in the 0.3–3 µm range to reach the sensitive pyranometer surface (Figure I.4.3). Some types of pyranometer have the entire surface blackened with half the thermojunctions attached to it, with the other junctions located so that they sense the slowly varying reference temperature of a large, shielded brass block. Other types have a sensitive surface that consists of white and black painted surfaces, with thermojunctions attached to both.

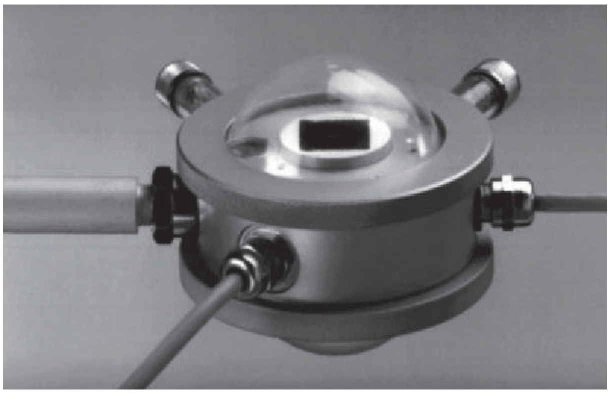

Figure I.4.3. Pyrradiometer (detail of the sensor)

Long-wave radiation

Long-wave radiation is measured indirectly with flat-plate radiometers. These instruments are not selective in response to different wavelengths and thus measure all wavelengths. The long-wave radiation is computed as the difference between the total radiation received from sun and sky as observed with a radiometer; the solar radiation is measured with a pyranometer at the same site.

One type of long-wave radiometer consists of a flat 5-cm^2 plate mounted horizontally in the exhaust of a small blower. The plate is a sandwich with a blackened aluminium upper surface and a polished aluminium lower surface. A thermopile measures the vertical temperature gradient across an insulating sheet that forms the centre layer of the sandwich. The thermopile voltage is proportional to the heat flow down through the plate, which in turn is proportional to the energy received at the blackened surface after deduction of the black-body radiation. To correct for the black-body radiation, a separate thermocouple measures the black-surface temperature. The function of the blower exhaust is to minimize the effects of wind on the calibration coefficient of the device.

Another type of instrument, a net pyrradiometer, measures the difference between total (short-wave and long-wave) incoming (downward) and outgoing (upward) radiation. The instrument consists of a horizontally mounted plate with two blackened surfaces. Half the junctions of a thermophile are attached to the upper surface and the others are attached to the lower surface, so that the thermopile output is proportional to net radiation in the 0.3–100 µm band. These instruments are divided into two types: those that are ventilated and those that are shielded to reduce convective heat transfer from the sensing element. Instruments should be mounted at least 1 m above representative vegetation cover.

Air temperature

Air temperature should be measured 2 m above the water surface near the centre of the reservoir. For small reservoirs, the air temperature may not be greatly modified in its passage across the water surface, in which case satisfactory measurements can be made at an upwind shore site.

Although observations of air temperature at intervals of one, four or six hours may be satisfactory, continuous records are desirable, especially in connection with humidity measurements. Electrical thermographs, utilizing thermocouple thermometers, are suitable for recording on the multichannel recording potentiometers used for radiation measurements.

In measuring air temperature, thermometers must be shaded from the sun without restricting natural ventilation. Special radiation shields have been designed for thermocouple thermometers. Measurements of air temperature should be accurate to within ±0.3°C.

Water-surface temperature

Several types of thermometers, such as mercury-in-glass or mercury-in-steel (including maximum and minimum and reversing thermometer), platinum-resistance or thermistor elements with electronic circuit and meter or recorder and thermocouple thermometers, with voltmeter, with or without recorder, are used for the measurement of water temperature.

Particular applications will determine which thermometer is most suitable. For example, direct observations are best carried out with a mercury-in-glass thermometer, whereas continuous records may be obtained with resistance or thermocouple elements.

Thermographs, which produce a continuous record of temperature, usually comprise a mercury-in-steel sensing element immersed in the water, which is connected to a circular or cylindrical chart recorder with a Bourdon-tube transducer. Care should be taken in the installation of thermographs to ensure that measurements taken are representative of the water temperature (Herschy, 1971).

In the case of automatic stations where the measurement, which will usually include other variables, is recorded on a magnetic tape or transmitted over direct wire or radio-telemetry systems, the platinum-resistance or thermistor thermometers are used most frequently. As these have no moving parts, they are more reliable and offer greater accuracy and sensitivity of measurement. The sensing element is usually connected to a Wheatstone-bridge circuit and an electronic amplifier to produce an output signal that is suitable for recording or transmission.

In general, the precision required for the measurement of water temperature is ±0.1°C, except for special purposes where a greater accuracy may be required. However, in many circumstances precision of observation of ±0.5°C is adequate and there are many instances where statistical temperature data are quoted to the nearest 1°C. Thus, it is important to specify the operational requirement so that the most suitable thermometer is selected.

Humidity or vapour pressure of the air

Humidity measurements are made at the same location as air temperature. Psychrometers utilizing thermocouple thermometers are best suited for recording purposes. The thermocouple thermometers described in the preceding section on Air temperature, with an additional thermocouple thermometer to record wet-bulb temperatures, will give adequate results. Wet-bulb thermocouples require a wick and a reservoir that should be so arranged that the water will arrive at the wet-bulb temperature. Wet-bulb thermometers must be shielded from radiation and must, at the same time, maintain adequate ventilation to obtain a true wet-bulb temperature. A shield similar to the one used for air temperatures will provide adequate ventilation if wind speeds are greater than 0.5 ms^{-1}. In practice, the shield for the wet-bulb thermometer is placed just below the air temperature shield.

If measurements of dry- and wet-bulb temperatures are made to within ±0.3°C, the relative humidity should be within ±7 per cent for moderate temperatures. This is adequate for determining vapour pressure.

Wind

Wind speed should be measured near the centre of the lake or reservoir at a height of 2 m above the water surface. In practice, an anchored raft is used to support the instrumentation.

Any type of standard anemometer suitable for remote indication or recording should be adequate to determine the average daily wind speed. The three-cup rotor fan anemometers are most suited for remote recording. Accuracy of wind measurements by the three-cup or fan anemometers is usually within ±0.5 m s^{-1}, which is considered acceptable for evaporation measurements.

If a totalizing anemometer is used, provision must be made to read the counter at fixed intervals (preferably daily). If an electrical-contact anemometer is used, a recorder must be provided. This can be done by an electrical event marker on the margin of the temperature chart.

4.1.4 Measurement of evapotranspiration

Soil evaporimeters and lysimeters

Evapotranspiration can be estimated by the use of soil evaporimeters and lysimeters, by the water-budget or heat-budget methods, by the turbulent-diffusion method, or by various empirical formulae based on meteorological data. Use of soil evaporimeters and lysimeters allows direct measurement of evapotranspiration from different land surfaces and evaporation from the soil between cultivated plants. These instruments are simple and accurate if all requirements concerning their installation and observational techniques are fulfilled. Transpiration of vegetation is estimated as the difference between measured evapotranspiration and contemporaneously measured evaporation from the soil.

Soil evaporimeters and lysimeters are categorized according to their method of operation:
(a) Weight based, which use mechanical scales to account for changes in water content;
(b) Hydraulic based, which use the hydrostatic principle of weighing;
(c) Volumetric based, in which water content is kept constant and evapotranspiration is measured by the amount of water added or removed.

There is no single standard instrument for measuring evapotranspiration.

General requirements for the location of evaporation plots are as follows:
(a) The site selected for the plot should be typical of the surrounding area with respect to irrigation, soil characteristics (texture, layering, genetical type), slope and vegetative cover;

(b) The evaporation plot should be located beyond the zone of influence of individual buildings and trees. It should be situated at a distance not less than 100 to 150 m from the boundaries of the field and not more than 3 to 4 km from the meteorological station. Soil monoliths for inclusion in evaporimeters and lysimeters should be taken from within a radius of 50 m of the plot, and the soil and vegetative cover of the monolith should correspond to those of the plot.

4.1.5 **Remote-sensing measurements of evaporation and evapotranspiration variables** [HOMS D]

Remote-sensing observations combined with ancillary meteorological data have been used in obtaining indirect estimates of ET over a range of temporal and spatial scales (Schulz and Engman, 2000). Recently there has been a lot of progress in the remote-sensing of parameters, including:
(a) Incoming solar radiation;
(b) Surface albedo;
(c) Vegetative cover;
(d) Surface temperature;
(e) Surface soil moisture.

Remote-sensing of evaporation variables

Measurements of radiation and air temperature are usually made at the same locations, either at the centre of the lake or reservoir or at an upwind shore station. This permits recording several items in sequence on a single multichannel recorder. Integrating devices are sometimes used with strip-chart recorders. These devices present a visual readout of the average value of each item for the time period for which evaporation is to be computed (usually 10 days or two weeks).

Remote-sensing of several important parameters used to estimate evaporation is made by measuring the electromagnetic radiation in a particular waveband reflected or emitted from the Earth's surface. The incoming solar radiation can be estimated from satellite observations of cloud cover primarily from geosynchronous orbits using Multispectral Scanner (MSS) in the visible, near-infrared and thermal infra-red parts of EMS (Brakke and Kanemasu, 1981; Tarpley, 1979; Gautier and others, 1980). The surface albedo may be estimated for clear-sky conditions from measurements covering the entire visible and near-infra-red waveband (Jackson, 1985; Brest and Goward, 1987). The surface temperature may be estimated from MSS measurements at thermal IR wavelengths of the emitted radiant flux (Engman and Gurney, 1991).

However, there has been little progress in the direct remote-sensing of the atmospheric parameters that affect ET, such as:
(a) Near-surface air temperature;
(b) Near-surface water vapour gradients;
(c) Near-surface winds.

Furthermore, remote-sensing has a potentially important role because of its areal coverage in the spatial extrapolation process of ET.

Remote-sensing of evapotranspiration variables

Recently, researchers have begun using satellite data (for example, Bastiaanssen and others, 1998; Choudhury, 1997; Granger, 1997) to estimate regional actual evapotranspiration. Remote-sensing of several important parameters used to estimate ET is made by measuring the electromagnetic radiation in a particular waveband reflected or emitted from the Earth's surface. Estimates of incoming solar radiation, surface albedo and surface temperature may be done by the same satellite measurements described in 4.1.3. The soil moisture may be estimated using the measurement of microwave properties of the soil (microwave emission and reflection or backscatter from soil). However, there are uncertainties in such soil moisture estimates due to previously mentioned factors such as surface roughness and vegetative cover.

The most practical remote-sensing approach for the future will include repetitive observations at the visible, near and thermal infra-red, and microwave lengths. Components for determining the sensible heat flux will be measured by the EOS instruments. The latent heat flux cannot be measured directly but EOS instruments will provide some sampling capability. Furthermore, the future programme such as EOS should provide the necessary data for evaluating ET on local, regional and global scales.

4.2 ESTIMATING EVAPORATION FROM FREE SURFACES

4.2.1 **General** [HOMS I45]

Evaporation from water surfaces can be determined by various methods, such as:
(a) Water budget;
(b) Energy budget;
(c) Mass transfer methods;

(d) Combination methods;
(e) Empirical formulae.

Any of the methods described can be employed to determine evaporation. Usually, instrumentation for energy-budget and mass-transfer methods is quite expensive and the cost to maintain observations is substantial. For these reasons, the water-budget method and use of evaporation pans are more common. The pan method is the least expensive and will frequently provide good estimates of annual evaporation. Any approach selected is dependent, however, on the degree of accuracy required. As the ability to evaluate the parameters in the water budget and energy budget improves, so also will be resulting estimates of evaporation.

4.2.2 Water budget

The method is based on the continuity equation and can be utilized for the purpose of computing evaporation as:

$$E = I - O - \Delta S \qquad (4.2)$$

where E = evaporation, I = inflow, O = outflow and ΔS = change in storage.

By adding the suffixes s and g to the various components in equation 4.2 to denote vectors originating above and below ground surface respectively, the equation can be expressed as:

$$E_s = P + R_1 - R_2 - R_g - T_s - F - \Delta S_s \qquad (4.3)$$

where E_s = reservoir evaporation, P = precipitation, R_1 = surface runoff coming into the reservoir, R_2 = surface runoff going out of the reservoir, R_g = groundwater inflow, T_s = transpiration loss, F = infiltration (or seepage) and ΔS_s = change in storage.

If the net transfer of seepage ($R_g - F$) = O_s and the transpiration term T_s equals zero, then equation 4.3 can be rewritten:

$$E_s = P + R_1 - R_2 + O_s - \Delta S_s \qquad (4.4)$$

All the terms are in volumetric units for a time period of interest that should be not less than a week. The water-budget method, although having the obvious advantage of being simple in theory, has the disadvantage in that the errors in the measurement of the parameters used in equation 4.4 are reflected directly in the computed amounts of evaporation. Therefore, it is not recommended that the method be applied to time periods of less than a month if the estimate of evaporation is expected to be within ±5 per cent of the actual amount.

Probably the most difficult term to evaluate is the seepage, F. This component can be estimated knowing the hydraulic conductivity of the lake bed and the hydraulic gradient. Nevertheless, it should be recognized that the water-budget method of determining evaporation will prove most successful when applied to relatively impervious lakes in which the seepage is negligible in comparison with the amount of evaporation.

To evaluate ΔS_s, an accurate area-capacity curve for the lake should be available. Even with these data, the bank storage component can introduce an error in the water budget. However, if the bank storage component is neglected, the water budget would not be useful on an annual cycle.

Although it is theoretically possible to use the water-budget method for the estimation of evaporation from any free surface, it is usually impractical to do so because of the effects of errors in measuring various parameters. Evaporation, estimated by this method, is residual and, therefore, may be subject to considerable error if it is small relative to other parameters.

In summary, the method is difficult and inaccurate under most conditions, particularly for short averaging time periods. Some of the most difficult parameters to measure are change in storage, seepage, groundwater flow and advected flows.

4.2.3 Energy budget

The energy-budget method illustrates an application of the continuity equation written in terms of energy. It has been employed to compute the evaporation from oceans and lakes, for example, at Elephant Butte Reservoir in New Mexico (Gunaji, 1968). The equation accounts for incoming and outgoing energy balanced by the amount of energy stored in the system. The accuracy of estimates of evaporation using the energy budget is highly dependent on the reliability and preciseness of measurement data. Under good conditions, average errors of perhaps 10 per cent for summer periods and 20 per cent for winter months can be expected.

The energy-budget equation for a lake may be written as (Viessman and others, 1989):

$$Q_0 = Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w \qquad (4.5)$$

where Q_0 = increase in stored energy by the water, Q_s = solar radiation incident at the water surface, Q_r = reflected solar radiation, Q_a = incoming long-wave radiation from the atmosphere, Q_{ar} = reflected long-wave radiation, Q_{bs} = long-wave radiation emitted by the water, Q_v = net energy advected (net energy content of incoming and outgoing water) into the water body, Q_e = energy used in evaporation, Q_h = energy conducted from water mass as sensible heat and Q_w = energy advected by evaporated water.

All the terms in equation 4.5 are in watt per square metre per day (W m^{-2}day). Heating brought about by chemical changes and biological processes is neglected, as it is the energy transfer that occurs at the water–ground interface. The transformation of kinetic energy into thermal energy is also excluded. These factors are usually very small, in a quantitative sense, when compared with other terms in the budget if large reservoirs are considered. As a result, their omission has little effect on the reliability of results.

Each of the various terms in the energy-budget equation is either measured directly or computed from known relationships. The procedure used in evaluating each term is described below.

The terms of equation 4.5 that can be measured are Q_s, Q_r and Q_a, and the net radiation balance is:

$$R_f = Q_s - Q_{sr} + Q_a - Q_{ar} - Q_{bs} \tag{4.6}$$

All of the above values are expressed in W m^{-2}.

Detailed descriptions of the instruments and measuring techniques concerning the above-mentioned elements can be found in 4.1.3, 4.1.4 and 4.1.5, or in the *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8).

Reflected long-wave radiation (Q_{ar}) may be taken as 3 per cent of the long-wave radiation received by the water surface.

Long-wave radiation emitted by the water (Q_{bs}) is computed according to the Stefan–Boltzmann law for black-body radiation, with an emissivity factor of 0.970 for water. The equation for computing radiation emitted by the water surface is:

$$Q_{bs} = 0.97\sigma\theta^4 \tag{4.7}$$

where Q_{bs} is the radiation emitted by the water surface in W m^{-2}, σ is the Stefan-Boltzmann constant (5.67×10^{-8} *W* m^{-2} $°K^{-4}$), and θ is the temperature of the water surface in °K. For computing purposes, the average temperature of the water surface, as recorded near the centre of the reservoir, is determined for each period of study. The temperature is converted to °K, and the average radiation emitted by the water surface is computed for the period of study in W m^{-2}.

The thermal energy of the volume of water in the reservoir for a given date is computed from a temperature survey made on that date. These temperature measurements, which should be accurate to within 0.1°C, are usually made at biweekly or monthly intervals. The reservoir may be divided into several layers from the surface to the bottom. The volume of water for each of the layers is determined from the stage–volume relationship. All temperature observations made in a particular layer are averaged to obtain a mean temperature for that volume of water.

The summation of the products of volume and temperature (assuming a base temperature of 0°C) will give the total energy for that particular date. Density and specific heat are considered as unity for the range of temperatures that occur in the reservoir. In order to determine the energy utilized in evaporation, Q_e changes in energy storage resulting from advection of energy in the volumes of water entering or leaving the reservoir must be evaluated. Again, a base temperature of 0°C is usually chosen in computing the amount of energy in these volumes. Their temperatures are determined by observation or recordings (4.1.3) depending on the variation of temperature with the rate of flow. If the temperature of the water changes with the rate of flow, the mean temperature of the volume should be weighted according to the rate of flow. The temperatures of bank storage and net seepage are considered as being equal to the mean annual air temperature. This assumption is admittedly subject to error, but is not considered serious if the surface inflow is a large item in the water budget.

If precipitation is a significant item in the water budget, then the energy of this volume of water must be taken into account. The temperature of rainfall is assumed to be that of the wet bulb at the time of rainfall. In computing the energy for each of these volumes, centimetre-gram-second units are used, and density and specific heat are considered as unity for the range of temperatures that occur in these volumes. The product of temperature times volume will give the amount of energy for each volume in joules (net energy advected, Q_v). The difference between the computed energies of stored water for the thermal surveys made at the beginning and end of the period of study determines the change in energy storage (Q_0).

During winter months when ice cover is partial or complete, the energy budget only occasionally yields adequate results because it is difficult to measure reflected solar radiation, ice surface temperature and the areal extent of the ice cover. Daily evaporation estimates based on the energy budget are not feasible in most cases because reliable determination of changes in stored energy for such short periods is impractical. Periods of one week or longer are more likely to provide satisfactory measurements.

In using the energy-budget approach, it has been demonstrated that the required accuracy of measurement is not the same for all variables. For example, errors in measurement of incoming long-wave radiation as small as 2 per cent can introduce errors of 3–15 per cent in estimates of monthly evaporation, while errors of the order of 10 per cent in measurements of reflected solar energy may cause errors of only 1–5 per cent in calculated monthly evaporation. To permit the determination of evaporation by equation 4.5, it is common to use the following relation:

$$B = \frac{Q_h}{Q_e} \tag{4.8}$$

where B is known as Bowen's ratio (Bowen, 1926) and:

$$Q_w = \frac{c_p Q_e (T_e - T_b)}{L} \tag{4.9}$$

where c_p = the specific heat of water (cal/g°C) that is equal to 4186.8 J/kg°C, T_e = the temperature of evaporated water (°C) ; T_b= the temperature of an arbitrary datum usually taken as 0°C and L = the latent heat of vaporization (cal/g) that is equal to 2260 kJ/kg. Introducing these expressions in equation 4.5 and solving for Q_e, we obtain:

$$Q_e = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} - Q_o + Q_v}{1 + B + c_p(T_e - T_b) / L} \tag{4.10}$$

To determine the depth of water evaporated per unit time, the following expression may be used:

$$E = \frac{Q_e}{\rho L} \tag{4.11}$$

where E = evaporation (m sec^{-1}) and ρ= the mass density of evaporated water (kg m^{-3}).

The energy-budget equation thus becomes:

$$E = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} - Q_o + Q_v}{\rho \left\{ L(1 + B) + c_p(T_e - T_b) \right\}} \tag{4.12}$$

The Bowen ratio can be computed using:

$$B = 0.61 \frac{p(T_o - T_a)}{1000(e_o - e_a)} \tag{4.13}$$

where p = the atmospheric pressure (*mb*), T_o = the water-surface temperature (°C); T_a = the air temperature (°C), e_o = the saturation vapour pressure at the water-surface temperature (*mb*) and e_a = the vapour pressure of the air (*mb*).

This expression circumvents the problem of evaluating the sensible heat term, which does not lend itself to direct measurement.

Remote-sensing of several important parameters used to estimate evaporation is made by measuring the electromagnetic radiation in a particular waveband reflected or emitted from the Earth's surface as discussed earlier in 4.1.3.

Applicability of energy-budget approach

The points summarized below should be recognized first in order to apply the energy-budget approach for estimating the evaporation from free surfaces:

(a) The flow of heat from the bottom of the lake has not been accounted for. This, however, is important in the case of shallow lakes;
(b) Bowen's ratio is assumed to provide a sufficiently accurate estimate of Q_h;
(c) The approach neglects the effect due to radiative diffusivity, stability of the air and spray;
(d) The applicability of the approach hinges greatly on the ability to evaluate the advective energy components.

4.2.4 Mass-transfer method

The mass-transfer approach, as the name implies, is based on the determination of the mass of water vapour transferred from the water surface to the atmosphere. To better understand this, an insight into the physics of air movement is first discussed.

When air passes over land or water surfaces, the air thickness in the lower atmosphere may be divided into three layers: (a) the laminar layer near the surface; (b) the turbulent layer; and (c) the outer layer of frictional influence. The laminar layer, in which the air flow is laminar, is only of the order of a millimetre in thickness. In this layer the temperature, humidity and wind velocity vary almost linearly with height, and the transfer of heat, water vapour and momentum are essentially molecular processes. The overriding turbulent layer can be several metres in thickness depending on the level of turbulence. In this layer, temperature, humidity and wind velocity vary approximately linearly with the logarithm of height, and the transfer of heat, vapour and momentum through this layer are turbulent processes.

The mass-transfer approach is based on Dalton's aerodynamic law giving the relationship between evaporation and vapour pressure as:

$$E = k\,(e_s - e_a) \tag{4.14}$$

where E = direct evaporation, k = a coefficient and depending on the wind velocity, atmospheric pressure and other factors, e_s and e_a = saturation vapour pressure corresponding to the water-surface temperature and the vapour pressure of the air, respectively. Mean daily temperature and relative humidity may be used in determining mean vapour pressure e_a and mean saturation deficit ($e_s - e_a$). Equation 4.14 was originally proposed by Harbeck and Meyers (1970).

4.2.5 Combination of aerodynamic and energy-balance methods

Perhaps the most widely used method for computing lake evaporation from meteorological factors is based on a combination of aerodynamic and energy-balance equations:

$$E_i = \frac{R_n \Delta + E_a \gamma}{\Delta + \gamma} \tag{4.15}$$

where E_i is the estimated evaporation from a free-water surface, $\Delta = \frac{e_s - e_{sz}}{T_s - T_z}$ is the slope of the saturation vapour-pressure curve at any temperature θ_a, which is tabulated as γ/Δ versus T_z in Brutsaert (1982, Figure 10.2), R_n is the net radiation, γ is the constant in the wet and dry bulb psychrometer equation, and E_a is the same expressed in equation 4.14.

The psychrometer constant γ for °C is the same constant of the Bowen ratio, and its value at 1000-mb pressure is 0.61. The net radiation R_n (in MJ m^{-2} day) can be estimated by the following equation:

$$R_n = \left(0.25 + 0.5\frac{n}{N}\right) S_0 - \left(0.9\frac{n}{N} + 0.1\right) \left(0.34 - 0.14\sqrt{e_d}\right)\sigma T^4 \tag{4.16}$$

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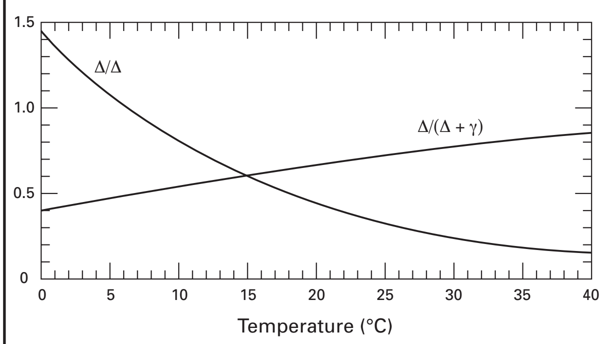


Temperature dependence of (γ/Δ) and $\Delta/(\Delta + \gamma)$ at 1000 mb
Adapted from Brutsaert (1982, Figure 10.2)

where n/N is the ratio of actual to possible hours of sunshine, S_0 is the extraterrestrial radiation (in MJ m^{-2} day), e_d is the actual vapour pressure of the air in mm of mercury, σ is the Stefan–Boltzmann constant, also expressed in equivalent evaporation in mm day^{-1}, and T is the mean air temperature (absolute) expressed in degrees Kelvin.

Although it may be necessary to use the above equation, it would be preferable to use measured values of solar and long-wave radiation.

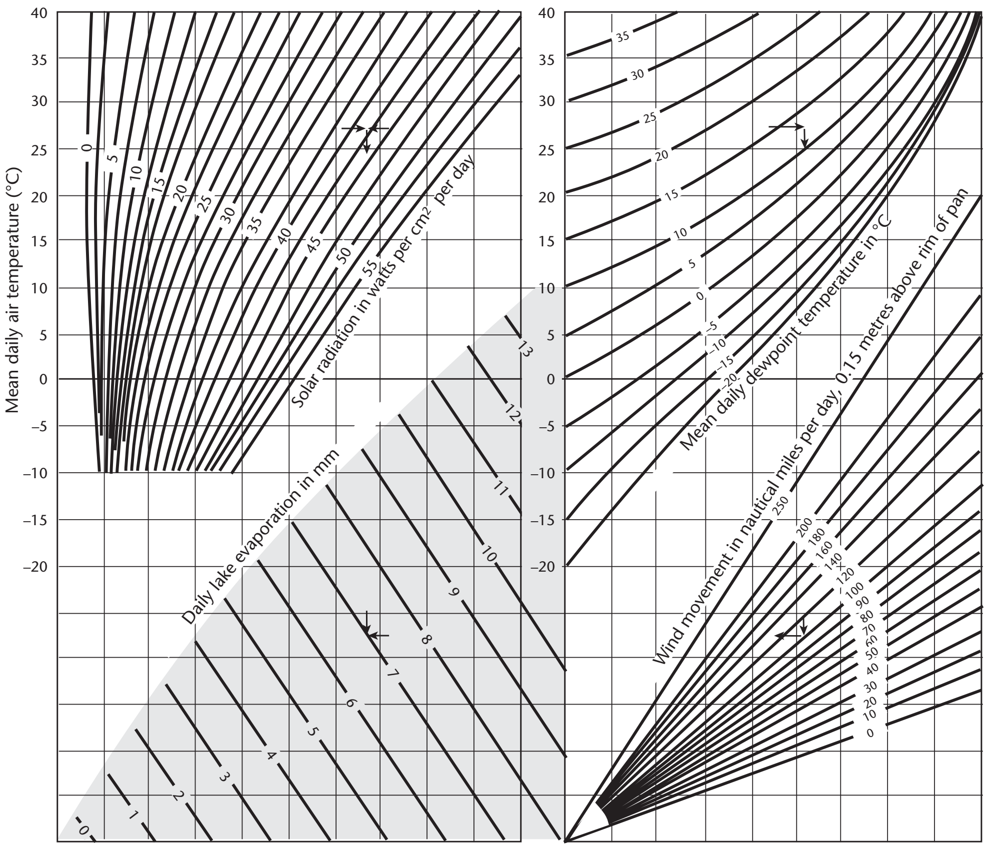
A similar approach was used by Kohler and others (1959) and a graphical presentation of the relationship is shown in Figure I.4.4. The meteorological observations of solar radiation, air temperature, dewpoint and wind movement at the anemometer height of a Class A pan are required for application of this technique. In the absence of solar-radiation observations, radiation may be estimated from the percentage of possible sunshine or cloud-cover data. Lake evaporation computed for short periods by this method would be applicable only to very shallow lakes with little or no advection of energy to the lake. For deep lakes and conditions of significant advection due to inflow and outflow, it is necessary to correct the computed lake evaporation for net advected energy and change in energy storage. These terms are described under the energy-budget method in 4.2.3. However, all of the advected energy and change in energy storage is not utilized for evaporation. The portion of this energy used for evaporation can be obtained from a relationship such as shown in Figure I.4.5. Observations of water-surface temperature and wind movement at 4 m above the water surface are required for application of this relationship. Reliable estimates of weekly or monthly lake evaporation can be obtained by this approach only if an evaluation is made of the energy-advection and storage factors.

4.2.6 **Extrapolation from pan measurements** [HOMS C46]

The evaporation from pans exposed in or on the ground is influenced by the characteristics of the pan. Sunken pans are subject to undetected leaks, accumulation of debris on the water surface, and boundary conditions with the soil different from those of a large lake. Pans exposed above the ground are subject to heat exchange through the sides and to other effects that do not occur in lakes. Floating pans are subject to splash-in and splash-out, and are costly to install and operate.

Pans have much less heat storage than lakes and tend to experience a different annual cycle of evaporation, with pan-evaporation extremes occurring earlier in the season. Reliable estimates of annual lake evaporation can be obtained by multiplying the annual pan evaporation by the appropriate pan-to-lake coefficient. These estimates will be reliable only if it can be assumed that, on an annual basis, any energy advected to the lake is balanced by a change in heat storage. The pan-to-lake coefficient for a particular pan is determined by comparison with actual lake evaporation, if available, or more commonly by comparison with a pan large enough to simulate a lake (sunken pans 4 m or more in diameter). The coefficient for a specific pan is also dependent, to a degree, upon the climatic regime, that is, different for arid or humid conditions. For an evaporation pan to serve as a valid index to lake evaporation, the exposure of the pan should avoid the environmental effects of the lake. Such an exposure would be near the lake, but on the side toward the prevailing wind direction. An island exposure would not be satisfactory.

One method for determining the climatic variation of the pan coefficient is by field comparisons with large pans under the various conditions. This method is applied in the Commonwealth of Independent States with the GGI-3000 and 20-m^2 tanks. The pan-to-lake coefficients thus derived for



Note: The International Pyrheliometric Scale, which became effective in the United States on 1 July 1957, provides values that are 2.0 per cent less than those previously obtained. Therefore, for computations based on data subsequent to 1 July 1957, increase radiation values by 2 per cent

Figure I.4.4. Lake–evaporation relationship

the GGI-3000 range between 0.75 and 1.00. For estimates of monthly average evaporation, the coefficient for a floating GGI-3000 evaporation pan is estimated by the following equation:

$$\alpha = 0.8\,\frac{e_0 - e_{200}\beta}{e'_0 - e_{200}\beta} \tag{4.17}$$

where e_o is the average monthly vapour pressure, in hPa, estimated from the surface temperature of water body, e'_o is the average monthly vapour pressure, in hPa, estimated from surface-water temperature in the floating GGI-3000 pan, e_{200} is the average monthly vapour pressure at 200 cm above the water surface, in hPa, β is a correction factor for the area of a water body, and γ is a factor that depends on the distance *l* along the average direction of wind from the shore to the pan (fetch).

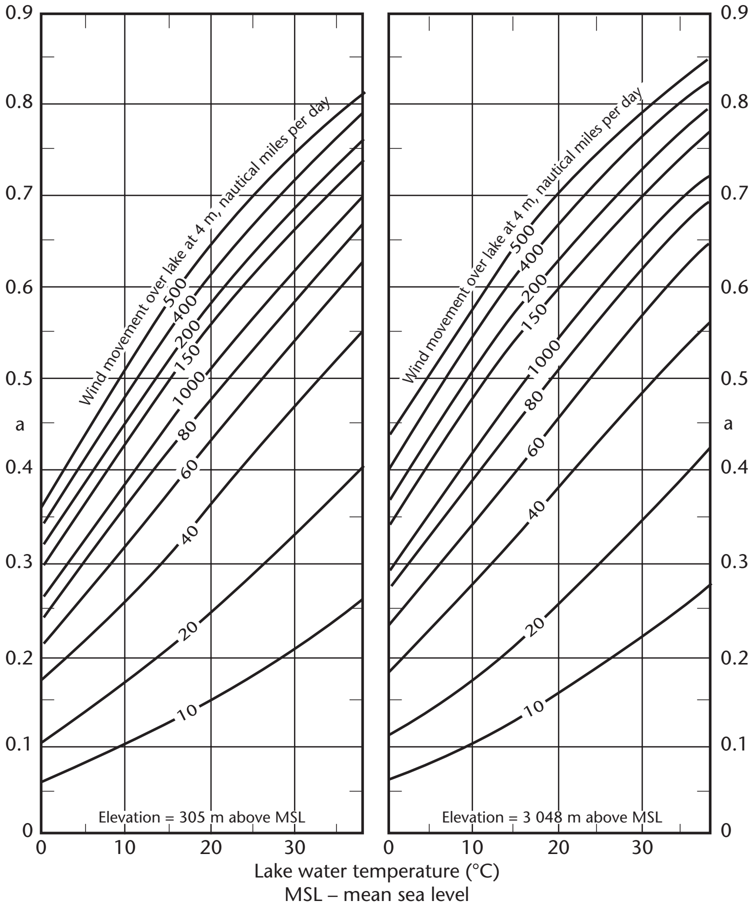
The ratio, β/γ, needs to be determined only for water bodies located in tundra, forest and forest-steppe zones and when the pan is located at a distance of up to 500 m from shore. In all other cases, this ratio is assumed to be equal to 1. For water bodies of approximately round or square shape, β is determined from the area of the water surface by using Table I.4.1.

Table I.4.1. Determination of β

Area of water body (km^2)	0.01	0.05	0.1	0.5	1.0	2.0	5.0
Correction factor β	1.03	1.08	1.11	1.18	1.21	1.23	1.26

For water bodies of irregular shape (long with islands and gulfs), the area used is that of an assumed circle with a diameter equal to an average distance, *l*, weighted with the frequency of wind direction in per cent from the eight points of the compass. The weighted distance can be computed by the equation:

$$\overline{l} = \frac{1}{100}\, i \sum_{i=1}^{i=8} l_i N_i \tag{4.18}$$



MSL – mean sea level

Figure I.4.5. Proportion of advected energy into a lake that is used for evaporation

where N_i is a frequency of wind direction from the eight points, in per cent; γ can be determined from Figure I.4.6.

Another method is the adjustment of the pan evaporation for heat gain or loss through the sides and bottom. An example of this method is the technique in estimating evaporation by using data from the Class A evaporation pan. In humid seasons and climates, the pan water temperature is higher than the air temperature, and the pan coefficient may be 0.80 or higher. In dry seasons and arid areas, the pan water temperature is less than air temperature, and the coefficient may be 0.60 or less. A coefficient of 0.70 is assumed to be applicable when water and air temperatures are equal. The relationships for estimating lake evaporation by adjusting Class A pan evaporation for heat gain or loss are shown in Figures I.4.7 and I.4.8. Owing to the important variation of wind with height, standard instrument heights are an essential requirement of the Class A station.

To obtain short-period estimates of lake evaporation with the pan method, it is also necessary to evaluate the net energy advection to the lake and change in energy storage as described in 4.2.3. It is useful to have pan evaporation near a lake or reservoir as a source of alternative data in the absence of other meteorological data and to help verify estimates made by the energy-budget and aerodynamic methods.

4.2.7 Empirical formulae

The energy-budget and mass transfer methods, though theoretically sound, require data which, for many studies, are not readily available. Moreover, in many cases even the economics of acquiring such data through instrumentation of the lake is also questionable. Thus, one has to make use of empirical formulae to obtain estimates of evaporation. Many empirical formulae to obtain estimates of evaporation have been developed (Mutreja, 1986) either on the basis of the energy-budget or mass transfer method. However, most of the equations are based on the simple aerodynamic equation given as equation 4.14.

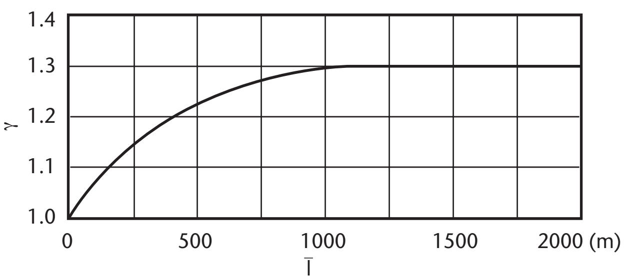


Figure I.4.6. Factor γ and $\bar{l}$ relationship

A few of the more common of these empirical formulae used for estimating the evaporation from lake surfaces are given below:

Penman's formula, United Kingdom – small tank (Penman, 1948)

$$E(\text{cm day}^{-1}) = 0.89\,(1 + 0.15U_2)\,(e_s - e_a) \qquad (4.19)$$

where U_2 = the wind speed at 2 m above the water surface, e_s = saturation vapour pressure at water surface temperature and e_a = vapour pressure of the air at the specified height.

Marciano and Harbeck's formulae, United States (Marciano and Harbeck, 1954)

$$E(\text{cm day}^{-1}) = 0.0918U_8(e_s - e_8) \qquad (4.20)$$

$$E(\text{cm day})^{-1} = 0.1156U_4(e_s - e_2) \qquad (4.21)$$

Kuzmin Formula, the then Union of Soviet Socialist Republics (Kuzmin, 1957) – reservoirs with surface >20–100 m

$$E(\text{cm month}^{-1}) = 15.24\,(1 + 0.13U_s)\,(e_s - e_a) \qquad (4.22)$$

United States Geological Survey (USGS), United States and Bureau of Reclamation's formula (USGS, 1977)

$$E(\text{cm/year}^{-1}) = 4.57T + 43.3 \qquad (4.23)$$

where T = mean annual temperature in °C

Shahtin Mamboub's formula, Egypt (Mutreja, 1986)

$$E(\text{cm day}^{-1}) = 0.35(e_s - e_a)\,(1 - 0.15U_2) \qquad (4.24)$$

where e_s = saturated vapour pressure at the water surface temperature (cm Hg^{-1}) and e_a = actual vapour pressure (cm Hg^{-1})

Unless specified in the above equations the wind speed (U) is in km x h^{-1} and vapour pressure is in cm of mercury. Further, the subscripts attached to the terms refer to the height in metres at which the measurements are to be taken. Also, the vapour pressure term e is frequently taken as the saturated vapour pressure at the mean air temperature during the interval of measurement.

The equations require surface temperature of the body of water, which is very difficult to measure. If this is substituted by the mean air temperature, then the effects of advected energy to the lake on evaporation are not considered. This may introduce considerable error in the computed amounts of evaporation, as small errors in temperature induce large errors in the computations. Furthermore, the measurements of the wind speed and vapour pressure should be measured at the height specified by the equation being used. Usually, it is difficult to adjust the data collected at different heights because neither an accurate wind law nor laws defining the variation in humidity with height are currently available.

The greatest appeal for the use of these empirical formulae lies in the fact that they are simple to use with the standard available meteorological data. Nevertheless, the limitations of these empirical formulae must be clearly understood.

4.3 EVAPOTRANSPIRATION FROM DRAINAGE BASINS [HOMS I50]

4.3.1 General

Evapotranspiration considers evaporation from natural surfaces whether the water source is in the soil, in plants, or in a combination of both. With respect to the cropped area, the consumptive use denotes the total evaporation from an area plus the water used by plant tissues, thus having the same meaning as evapotranspiration. The determination of evaporation and transpiration as separate elements for a drainage basin is unreliable. Moreover, their separate evaluation is not required for most studies.

Evapotranspiration is one of the most popular subjects of research in the field of hydrology and irrigation. Numerous procedures have been developed to estimate evapotranspiration. These

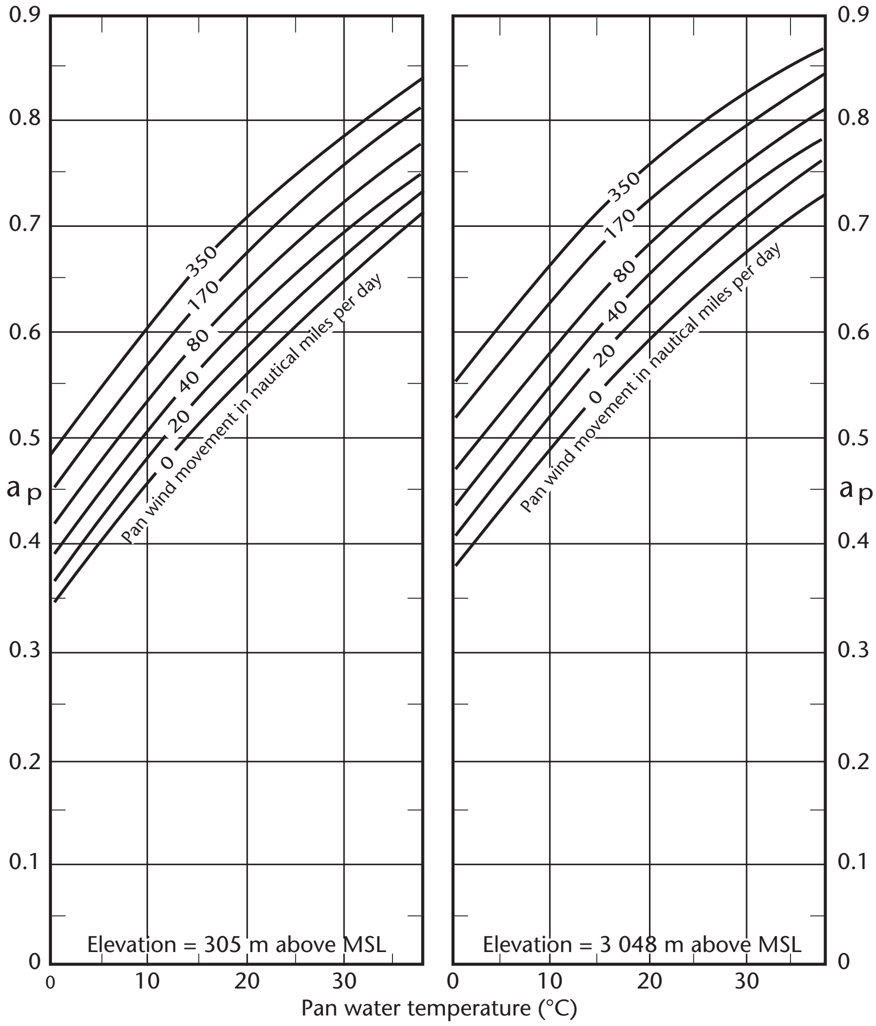


Figure I.4.7. Proportion of advected energy into a Class A pan that is used in evaporation

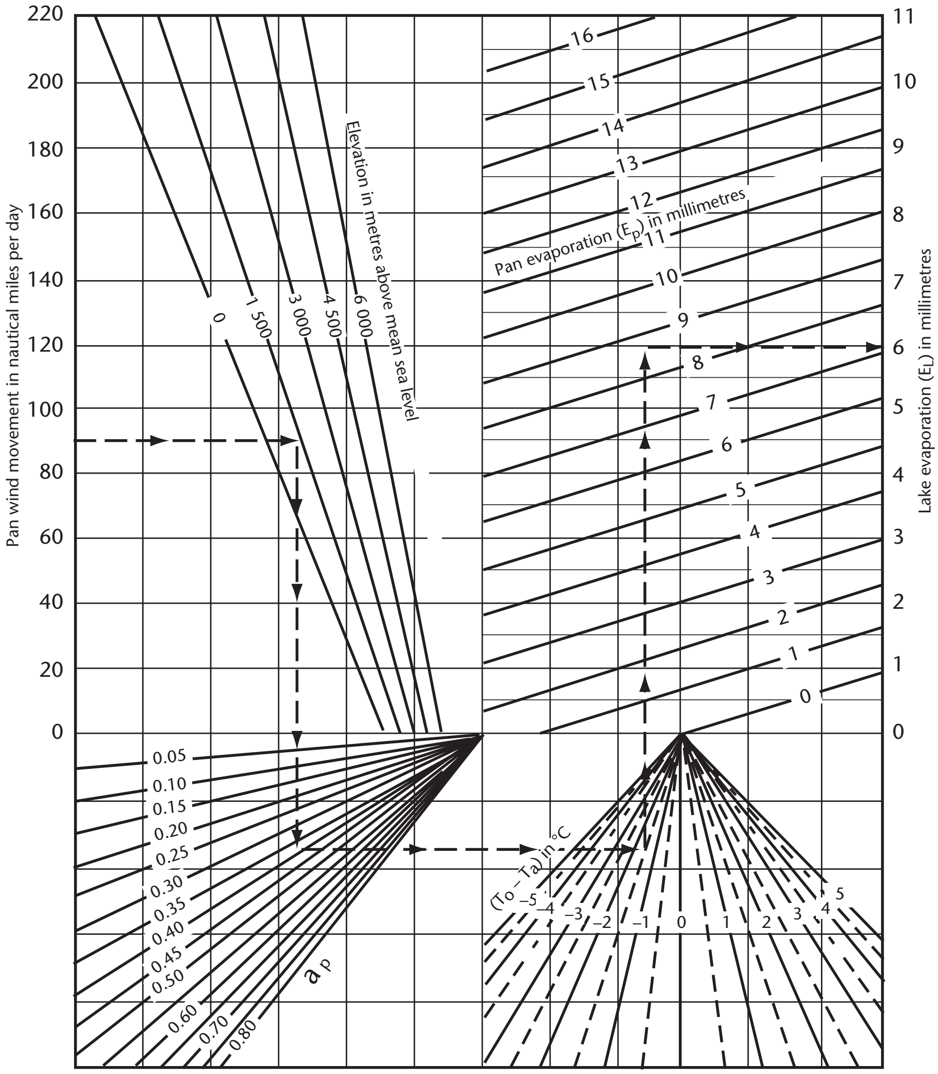


Figure I.4.8. Conversion of Class A pan evaporation into lake evaporation

fall in the categories of: (a) water balance methods, such as evapotranspirometers, hydraulic budget on field plots, and soil moisture depletion; (b) energy balance method; (c) mass-transfer methods, such as wind speed function, eddy flux and use of enclosures; (d) a combination of energy and mass-transfer methods, such as the Penman method; (e) prediction methods, such as the empirical equations and the indices applied to pan-evaporation data; and (f) methods for specific crops. These have been described in the *National Handbook of Recommended Methods for Water Data Acquisition* (USGS, 1977).

In the context of evapotranspiration, Thornthwaite and Holzman (1941) introduced the term "potential evapotranspiration" to define the evapotranspiration that will occur when the soil contains an adequate moisture supply at all times, that is, when moisture is not a limiting factor in evapotranspiration. The prediction methods estimate potential evapotranspiration. Most other methods apply to estimation of actual evapotranspiration under the condition of sufficient water at all times. The actual evapotranspiration from potential evapotranspiration is derived using a simple soil moisture function, $f(\phi)$ (Saxton and others, 1986):

$$\lambda E_{actual} = f(\phi)^{*} \lambda E \qquad (4.25)$$

where λE_{actual} is the actual evapotranspiration and the soil moisture function is a dimensionless variable estimated by a simple linear model. The soil moisture function is defined by the following:

$$f(\phi) = \mathrm{M/Field\ capacity} \qquad (4.26)$$

where M is soil volumetric moisture at 20-cm depth (at rooting zone). Field capacity can be defined as the percentage of water remaining in a soil two or three days after it has been saturated and after free drainage has practically ceased. It has been shown (Brandes and Wilcox, 2000) that simple linear models of the evapotranspiration/soil moisture process are appropriate for hydrological modelling.

4.3.2 Water-budget method

The water-budget approach can be used to estimate evapotranspiration, ET, when precipitation, P, stream runoff, Q, deep seepage, Q_{ss}, and changes in storage, ΔS, can be measured or estimated. The equation is:

$$ET = P - Q - Q_{ss} \pm \Delta S \tag{4.27}$$

The annual evapotranspiration from a basin for a water year can be estimated as the difference between precipitation and runoff if it can be established by hydrogeological studies that deep seepage is relatively insignificant. The date chosen for the beginning and ending of the water year should coincide with the dry season, when the amount of water in storage is relatively small and the change in storage from year to year is negligible.

If evapotranspiration is to be estimated for a shorter period, such as a week or a month, the amount of water storage in the ground and in the stream channel must be measured. This is feasible only on small basins, and application of the water-budget approach for such short periods is generally limited to experimental plots or catchments of a few acres.

For average annual evapotranspiration, the change in storage is usually negligible, and evapotranspiration can be estimated by the difference between average annual precipitation and average annual runoff.

The various terms of the above equation can be measured by conventional methods. The precipitation measurements can be made by a network of raingauges. For this purpose non-recording raingauges are adequate. The number of such raingauges would depend upon the expected variability of precipitation over the catchment. The streamflow measurements can be done by continuous measurement (Chapter 5). The change in water storage in the ground can be measured in two separate components, that is, the saturated and unsaturated components. For this purpose measurement of water table elevation in wells and measurement of soil moisture in the saturated zone are required. The elevation of the water table can be determined by measuring the distance from reference point to the water surface in wells at the end of each time period for which evapotranspiration is to be computed. The change in volume of water storage is equal to the average change in water elevation x the specific yield of the formation x the area of the catchment. Soil-moisture profiles from the saturation level (or to a point of constant soil moisture in arid regions) to the ground surface should be measured at the end of each computation period at a number of points over the catchment. The gain or loss of soil moisture during the period can then be computed. The amount of water that moves from or to the catchment as deep seepage cannot be measured directly. A hydrogeological study of the hydraulic characteristics of the underlying formations should indicate the relative magnitude of this flow, which must be considered when choosing the experimental area. This item should be small enough so that it can be neglected in water-budget studies.

4.3.3 Energy-budget method

This method (WMO, 1966) may be applied for the estimation of evapotranspiration when the difference between radiation balance and the heat flux into the soil is significant and exceeds the errors of measurement (4.2). This method is applied for estimation of evapotranspiration for periods of not less than 10 days. For shorter periods, the estimation of evapotranspiration by the energy-budget method is rather difficult.

Assuming that the surface energy balance equation is the primary boundary condition to be satisfied in computing ET, there are three techniques to solve the energy-balance equation. The first technique uses semi-empirical methods, the second employs analytical methods and the third utilizes numerical models.

The semi-empirical methods represent an effort to obtain a manageable model to estimate ET. These modern operational approaches are derived chiefly from Penman's original formulation, which is a combination of the diffusion and energy-balance approaches (Bailey, 1990). The Jackson model (Jackson and others, 1977) was later evaluated using empirical and theoretical results (Seguin and Itier, 1983). The energy-balance model is integrated over a 24-hour period and thus assumes that the soil heat flux is negligible. Furthermore, observations (Itier and Riou, 1982; Brunel, 1989) suggest that the daily ratio of sensible heat flux to the net radiation flux, R_n, can be approximated by that ratio estimated near midday under clear sky conditions. With some further approximations the energy-balance model can be recast as:

$$LE = R_n - B\,(T_s - T_a)_i + A \tag{4.28}$$

where LE is the latent heat flux (evapotranspiration, ET), T_s is the surface temperature estimated remotely, say from a satellite-based thermal IR sensor, T_a is the near-surface air temperature obtained from a nearby weather station, the subscript i represents the "instantaneous" observation by the satellite over the area of interest, and A and B constants which vary with location (Caselles and Delegido, 1987). In practice, however, A and B vary with a wide range of both meteorological and surface factors (Bailey, 1990). This expression and derivatives of it have been tested and shown to produce reasonable estimates of daily *ET* (Brunel, 1989; Kerr and others, 1987; Nieuwenhuis and others, 1985; Rambal and others, 1985; Thunnissen and Nieuwenhuis, 1990; Riou and others, 1988). Although equation 4.28 is characterized by low demands for data provision and ease of operation, it is also characterized by limited spatial and temporal areas of application together with poor accuracy especially in the presence of cloud when using satellite thermal infra-red methods to obtain T_s (Bailey, 1990).

According to WMO, Germany is utilizing NOAA AVHRR data for input into numerical evaporation models in small-scale agricultural areas. Satellite data include vegetation, land-surface temperature gradients, soil moisture, diurnal temperature variations and solar irradiance. Extrapolation of the model results are to be tested (WMO, 1992*a*).

4.3.4 Aerodynamic approach

The application of this method (WMO, 1966) for the estimation of evapotranspiration is difficult because of the lack of reliable methods to determine the turbulent-exchange coefficient (4.2). Thus, it is seldom used. It is used only for approximate estimation of evaporation.

In some countries, evapotranspiration is estimated by empirical methods, the Penman method and the Thornthwaite formula. Penman's method is used in conditions of sufficient moisture, and the Thornthwaite formula (Thornthwaite and Holzman, 1941) is applied for regions with climatic conditions similar to those of the middle Atlantic coast of the United States on which this formula was based.

In the Commonwealth of Independent States, Konstantinov's method (Konstantinov, 1966) is applied for the estimation of evaporation based on observations of temperature and humidity of the air in a psychrometer shelter at 2 m above the ground. This method is mainly applicable for the computation of long-term mean monthly, seasonal or annual evapotranspiration.

4.3.5 Penman–Monteith method

The combination equation 4.14 represents the energy budget at the land surface and the transfer of water vapour and heat between the surface and the atmosphere. The Penman–Monteith method (Monteith, 1965) introduces aerodynamic and surface resistances. The former describes the effect of surface roughness on heat and mass transfer and the latter describes the resistance to the flow of water vapour between the evaporating surface and the air. Surface resistance for water surfaces is zero. In the case of vegetation, the surface resistance represents biological control of transpiration and is largely controlled by stomatal resistance. For drying soil, the surface resistance depends on soil moisture availability. This method may be used on an hourly or daily basis. However, its use is restricted because it requires sub-models for the surface resistance.

The Penman–Monteith model is expressed as:

$$\lambda E = (\Delta\Delta + C_p \rho D / r_{aa}) / (\Delta + \gamma + \gamma\ (r_{cs} / r_{aa})) \qquad (4.29)$$

where r_{aa} is the aerodynamic resistance above the canopy, and r_{cs} is stomatal resistance of the canopy. For the Shuttleworth–Wallace model (Shuttleworth and Wallace, 1985), λE is separated into evaporation from the soil (λE_s) and transpiration from the canopy (λE_c), which are derived from the Penman–Monteith combination equations:

$$\lambda E_s = (\Delta\Delta_s + \rho c_p D_0 / r_{sa}) / (\Delta + \gamma (l + r_{ss} / r_{sa})) \qquad (4.30)$$

$$\lambda E_c = (\Delta\Delta(- A_s + \rho c_p D_0 / r_{ca}) / (\Delta + \gamma (l + r_{cs} / r_{ca})) \qquad (4.31)$$

where A_s is available soil energy, D_0 is vapour pressure deficit in the canopy, r_{sa} is the aerodynamic resistance between the substrate and canopy source height, r_{ca} is the boundary layer resistance of the vegetation, and r_{ss} is soil resistance. The aerodynamic resistance above the canopy (r_{aa}) and the aerodynamic resistance between the substrate and canopy source height (r_{sa}) are functions of leaf area index, eddy diffusivity decay constant, roughness length of the vegetation (function of vegetation height), zero plane displacement (function of vegetation height), a reference height above the canopy where meteorological measurements are available, wind speed, von Karman's constant, and roughness length of the substrate. D_0 is derived from the Ohm's law electrical analog for the vapour pressure and temperature difference between the canopy and the reference height above the canopy where fluxes out of the vegetation are measured. D_0 is a function of the measurable vapour pressure deficit at the reference height, D:

$$D_0 = D + (\Delta\Delta - r_{aa}\lambda E_c(\Delta + \gamma))/\rho c_p \qquad (4.32)$$

and D can thus be substituted for D_0 into the combination equations. The total evaporation from the crop, λE, for the Shuttleworth–Wallace model is the sum of the Penman–Monteith combination equations with D substituted for D_0:

$$\lambda E = C_c PMM_c + C_s PM_s \qquad (4.33)$$

where PM_c describes evaporation from the closed canopy, and PM_s describes evaporation from the bare substrate. The new Penman–Monteith equations have the form:

$$PM_c = \frac{(\Delta\Delta + (\rho\rho_p D - \Delta r_{ca} A_s) / (r_{aa} + r_{ca}))}{(\Delta + \gamma (1 + r_{cs} / (r_{aa} + r_{ca})))} \qquad (4.34)$$

$$PM_s = \frac{(\Delta\Delta + (\rho\rho_p D - \Delta r_{sa} A_s) / (r_{aa} + r_{sa}))}{(\Delta + \gamma (1 + r_{ss} / (r_{aa} + r_{sa})))} \qquad (4.35)$$

The coefficients C_c and C_s are resistance combination equations:

$$C_c = l/(l + R_c R_a/(R_s(R_c + R_a))) \qquad (4.36)$$

$$C_s = l/(l + R_s R_a/(R_p(R_s + R_a))) \qquad (4.37)$$

where

$$R_a = (\Delta + \gamma) r_{aa} \qquad (4.38)$$

$$R_s = (\Delta + \gamma) r_{sa} + \gamma r_{ss} \qquad (4.39)$$

$$R_c = (\Delta + \gamma) r_{ca} + \gamma r_{cs} \qquad (4.40)$$

4.3.6 Priestley–Taylor (radiation) method

The method of Priestley and Taylor (Priestley and Taylor, 1972) is based on the argument that, for large, wet areas, radiation controls of evaporation must dominate rather than advective controls. If the atmosphere remains saturated when in contact with the wet surface, then the latent-heat transfer (evaporation) may be expressed by:

$$\lambda E = \left(\frac{\varepsilon}{\varepsilon + 1}\right)(Q^* - G) \qquad (4.41)$$

where Q* is the available net radiation, G is the soil-heat flux, and ε equals $s\lambda/c_p$, with s equal to the slope of the saturation specific humidity curve, λ is the latent heat of vaporization, and c_p is the specific heat of water.

For equilibrium evaporation, it is proposed that:

$$\lambda E = \alpha \left(\frac{\varepsilon}{\varepsilon + 1}\right)(Q^* - G) \qquad (4.42)$$

with α = 1.26, an empirical constant. This expression is used as an estimate of potential evaporation in the absence of local advection. It also gives good estimates for evaporation from well-watered but not wet vegetation in much smaller regions.

4.3.7 Complementary method

The complementary method, first suggested by Bouchet (1963), is increasingly used in hydrological applications for large areas because it essentially uses standard climatic data.

The method considers that potential evaporation is as much the effect of the actual evaporation as its cause. Heat and moisture released from the surface will modify the temperature and humidity of the air above it. It has been suggested that the increase in potential evaporation observed when an area dries out may be used as a measure of the actual evaporation rate.

If actual evaporation E is reduced below the potential rate E_{po} for an extensive wet region, then an amount of energy Q would be released, so that:

$$\lambda E_{po} - \lambda E = Q \qquad (4.43)$$

This energy change will affect temperature, humidity, turbulence and hence evaporation. If the area is big enough so that the change in energy does not result in changes in the transfer of energy between the modified air mass and that beyond, Q should equal the increase in λE_p, the potential evaporation for the drying region.

Hence:

$$\lambda E_p - \lambda E_{po} = Q \qquad (4.44)$$

Therefore:

$$E + E_p = 2\,E_{po} \qquad (4.45)$$

Most applications of the complementary relationship (Morton, 1982) have been concerned with finding appropriate expressions for E_p and E_{po}. These may be estimated with equation 4.15 and the

Priestley–Taylor method given in 4.3.6, respectively. The approach does not consider advection and assumes Q to remain constant. Also, the vertical exchange of energy, that is, with air masses brought in by large-scale weather systems, is not considered.

4.3.8 Crop coefficient and reference evapotranspiration method

In 1998, *Crop evapotranspiration – Guidelines for computing crop water requirements* (FAO-56 report), recommended a new standard for reference crop evapotranspiration using the Blaney–Criddle, Penman, radiation and pan evaporation methods. The FAO-56 approach (FAO, 1998; Allen 2000) first calculates a reference evapotranspiration (ET_o) for grass or an alfalfa reference crop and then multiplies this by an empirical crop coefficient (K_c) to produce an estimate of crop potential evapotranspiration (ET_c). The ET_c calculations used the dual crop coefficient approach that includes separate calculation of transpiration and evaporation occurring after precipitation and irrigation events.

The FAO-56 Penman–Monteith method computes reference evapotranspiration from net radiation at the crop surface, soil heat flux, air temperature, wind speed and saturation vapour pressure deficit. The crop coefficient is determined from a stress reduction coefficient (K_s), a basal crop coefficient (K_{cb}) and a soil water evaporation coefficient (K_e). The K_{cb} curve is divided into four growth stages: initial, development, mid-season and late season. Field capacity and wilting point estimates determine soil water supply for evapotranspiration. The downward drainage of the topsoil is included but no upward flow of water from a saturated water table was considered, possibly causing some overprediction of water stress between the known irrigations. Water stress in the FAO-56 procedure is accounted for by reducing the value of K_s.

4.3.9 Large aperture scintillometer

Estimation of actual evapotranspiration using the energy-balance method requires knowledge of the sensible heat flux. According to the Monin–Obukhov similarity theory, the sensible heat flux, H, is related to the structure parameter of temperature, C_T^2. A large aperture scintillometer is an instrument to collect path-average values of C_T^2 (de Bruin and others, 1995). The scintillometer directs a light source between a transmitter and receiver and the receiver records and analyses fluctuations in the turbulent intensity of the refractive index of the air. These fluctuations are due to changes in temperature and humidity caused by heat and moisture eddies along the path of the light. Additional data on temperature, pressure and humidity are necessary to compute the characteristic parameter of the refractive index. This can then be converted to sensible heat flux. An important feature of the scintillometer technique is that although the measurement is along the path of the light beam, because of the effects of wind, this is actually an estimate of H over an area. The method therefore forms an intermediate level between the field scale measurements and the large area remote-sensing estimates.

4.4 EVAPORATION REDUCTION

4.4.1 From free surfaces

Evaporation losses from a fully exposed water surface are essentially a function of the velocity and saturation deficit of the air blowing over the water surface, and the water temperature. Evaporation losses are held to a minimum by:

(a) Exposing the least possible water-surface area. This in turn means that streams and reservoirs should be kept deep instead of wide;
(b) Covering the water surface;
(c) Controlling aquatic growth;
(d) Creating afforestation around reservoirs that would act as windbreakers. However, this method has been found to be useful under limited conditions for small ponds;
(e) Storing water underground instead of creating a surface reservoir. To accomplish this there are physical and legal problems in preserving the water so stored from adverse withdrawal;
(f) Making increased use of underground water;
(g) Integrated operation of reservoirs;
(h) Treatment with chemical water evaporation retardents (WER).

The first seven methods mentioned above are direct and easily understandable methods. However, the last method needs some explanation. This method comprises dropping a fluid on the surface of the water so as to form a monomolecular film. The problem with the film, however, is that it becomes damaged by wind and dust, and is too rigid to enable repair of the film thus damaged. Chemicals such as hexadecanol and octadecanol, of course, can be used for the purpose (Gunaji, 1965).

Studies by the Bureau of Reclamation indicate that evaporation may be suppressed by as much as 64 per cent with hexadecanol films in 1.22-m diameter pans under controlled conditions. Actual reduction on large bodies of water would, of course, be significantly less than this because of problems of maintaining the films against wind and wave action. Evaporation reduction to the extent of 22 to 35 per cent has been observed on small lakes of roughly 100 ha in size with reductions of 9 to 14 per cent reported on larger lakes (La Mer, 1963).

In Australia, evaporation reduction to the extent of 30 to 50 per cent has been observed on medium lakes of roughly 100 ha in size. Although the use of the monomolecular film is still in the research stage, its relative case means that some measure of evaporation control can be obtained through this technique.

4.4.2 From soil surface

There are various methods of controlling evaporation losses from soil (Chow, 1964).

(a) *Dust mulch*: This is an age-old practice in cultivation of soil to keep it loose on the surface. It is based on the theory that loosening the surface will permit rapid drying and reduce contact between soil particles. Rapid drying will develop dry soil to act as a blanket to suppress evaporation. Reducing points of contact between soil particles will lessen capillary rise.
It has been found that soil cultivation by tillage may be necessary only to kill weeds and keep the soil in a receptive condition to absorb water and deep tillage is futile as a means of overcoming drought or increasing yield. Experiments have also shown that mulching not only decreased the amount of water in the soil, but also caused loss of more moisture than in the bare, undisturbed soils. In tank and field trials it has also been found that mulching by thorough cultivation at weekly intervals failed to save soil moisture, but the surface shallow layer, by drying quickly, acted as a deterrent to further loss of moisture.
Since these early investigations, the results of many others have been published. Many agricultural experiment stations have studied this problem, resulting in conclusions similar to those mentioned. Various experiments have also indicated that the soil mulch can reduce moisture loss only when the water table, perched or permanent, is within the capillary rise of the surface;

(b) *Paper mulch*: Covering the soil with paper to reduce evaporation was widely used in the late 1920s, but is now rarely done as it has been found that the effect of paper mulch is confined to limited surface of soil, which again is due to condensation of water beneath the paper;

(c) *Chemical alteration*: Experiments in the early 1950s indicated that chemical alteration of the soil moisture characteristics may decrease evaporation. The addition of polyelectrolytes to soils decreases the rate of evaporation and increases the water available to plants;

(d) *Pebble mulch*: In China this method has been used for partial control of evaporation in some dry areas.

4.5 SOIL MOISTURE MEASUREMENT [HOMS E55]

4.5.1 General

Below the surface of the Earth there exists a huge reservoir of freshwater. This subsurface water can be divided into soil moisture, vadose water, shallow groundwater and deep groundwater. The zones of soil moisture and vadose water are together known as the zone of aeration. The amount of water held as soil moisture at any time is an insignificant amount by comparison with the Earth's total available water, but it is crucial to plant life and food production and thus vital to life.

Soil moisture can be defined as the water held in the soil by molecular attraction. The forces acting to retain water in the soil are adhesive and cohesive forces. These forces act against the force of gravity and against evaporation and transpiration. Thus, the amount of moisture in the soil at any given time is determined by the strength and duration of the forces acting on the moisture, and the amount of moisture initially present.

Natural sources of soil water such as rainfall and snow melt are normally greatly reduced during drought. Slope shape, gradient and soil surface roughness will affect soil water content since surface or subsurface run-on from adjacent upslope sites can add to the soil moisture, while surface runoff can remove water from a site. Evaporation, evapotranspiration and deep percolation beyond rooting depth are other factors that deplete soil moisture.

Hence, soil water content must be defined in specific quantitative terms to accurately indicate the amount of water stored in the soil at any given time. At saturation, after heavy rainfall or snow melt, some water is free to percolate down through the soil profile. This excess water is referred to as gravitational water and can percolate below the rooting depth of some plants. Here it is important to define some terms in relation to soil moisture. Field capacity is defined as the amount of water remaining in the soil after percolation has occurred. Wilting point is defined as the soil water content at which the potential of plant roots to absorb water is balanced by the water potential of the soil. The amount of water between field capacity and wilting point is generally considered plant available water content although plants can also extract gravitational water while it is available.

The moisture content of the soil is a key component in making irrigation scheduling decisions. The root zone serves as a reservoir for soil moisture. During the rainy season the moisture content is high, but at harvest time the soil is commonly depleted of moisture. Thus the measurement of soil moisture is an important factor in preventing overirrigation resulting in wastage of water and leaching of fertilizers or under-irrigation, that result in water deficit.

Soil moisture is measured in two distinctly different methods: quantitatively and qualitatively, which is an indication of how tightly the water is held by the soil particles.

4.5.2 Quantitative methods

4.5.2.1 Gravimetric method (Oven dry and weigh)

The gravimetric method is one of the direct methods of measuring soil moisture. It involves collecting a soil sample (usually 60 cm^3), weighing the sample before and after drying it, and calculating its moisture content. The soil sample is considered to be dry when its weight remains constant at a temperature of 105°C. Many different types of sampling equipment, as well as special drying ovens and balances, have been developed and used for this method.

The gravimetric method is the most accurate method of measuring moisture content in the soil and serves as the standard for calibrating the equipment used in all other methods. However, it cannot be used to obtain a continuous record of soil moisture at any one location because of the necessity of removing the samples from the ground for laboratory work.

Sample collection

The procedure for collecting a sample for the gravimetric method depends on whether the soil-moisture determination is to be based on the dry mass of the sample or on its volume for dry-mass determination, but not for volumetric determination. The sample can be disturbed for dry-mass determination, but not for volumetric determination. Soil sampling is fraught with difficulties if the soil is very dry or very wet or if it contains stones or other material that preclude easy cutting by the sampling equipment.

The technique and equipment used for sample collection should be such that the samples do not lose or gain moisture or otherwise become altered or contaminated during sampling and transportation. When sampling through a wet layer into a dry layer, care must be taken to keep the sampling equipment as dry as possible and to prevent water from running down the hole into the drier material. If there is free water in the soil, the measured moisture content probably will be less than the correct value because some water will drip off as the sample is removed from the ground, or some may be squeezed out by compaction during sampling.

When dry, hard, fine-textured sediments are encountered it is difficult to drive the core barrels or to rotate the augers. When dry, coarse-textured sediments are sampled, the sample may slide out at the end of the core barrel or auger as it is withdrawn. Stony soils are very difficult to sample, especially volumetrically, because of the likelihood of hitting a stone with the cutting edges of the equipment and because representative samples must be large. Soils that contain a considerable amount of roots and other organic matter also present difficulty.

The amount of soil taken for the gravimetric moisture determination of a gravel soil needs to be substantially more than for non-gravel soils and depends proportionally on the size and content of the gravel. Moisture is determined as a percentage by mass (weight). If multiplied by bulk density, moisture as a percentage of volume is obtained.

In soil-moisture sampling, it is essential that all sampling operations, as well as the transfer of samples to cans, and the weighing of the moist samples be done as rapidly as possible to minimize moisture losses. Many difficulties in the use of sampling equipment may be avoided if the equipment is kept clean and free of moisture and rust.

Description of samplers

Auger samplers (Figure I.4.9)

The simplest equipment for soil-moisture sampling is the hand auger. Hand augers, with shaft extensions of aluminium pipe, have been used in sampling to depths as much as 17 m. One of the most useful types of hand augers consists of a cylinder 76 mm in diameter and 230 mm long, with a 1.4-m extension pipe on the top and two curved, cutting teeth on the bottom. Because the barrel is a solid cylinder, the sample is not as likely to become contaminated from the side of the test hole. Thus, a good, representative, but disturbed, sample is obtained by using this equipment. For ease in sampling at depths greater than 1.5 m, 0.9 m extensions of 19-mm aluminium pipe are added, as needed (Figure I.4.10).

To obtain a sample by the hand-auger method, the auger has to penetrate usually about 80 mm of the material in order to fill the cylinder barrel. The auger is then raised to the surface, and the barrel is struck with a rubber hammer to jar the sample loose.

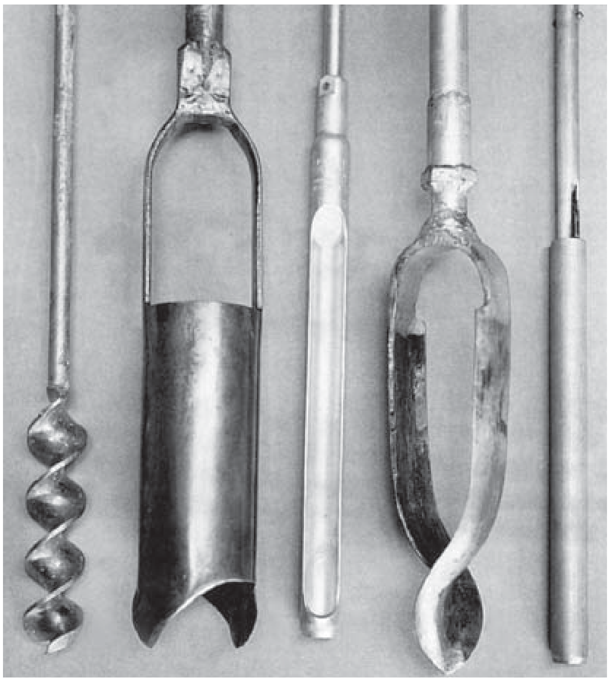


Figure I.4.9. Soil augers and tubes (left to right: screw or worm auger; barrel auger; sampling tube; Dutch mud auger; peat sampler)
(Source: http://soils.usda.gov/technical/manual/print_version/complete.html)

Tube or core-barrel samplers (Figure I.4.9)

A soil-sampling tube, core barrel or drive sampler offers an advantage in soil-moisture sampling as volumetric samples can be obtained for calculating moisture content by volume. Core samplers provide uncontaminated samples if the equipment is kept clean. Oil should never be used on the samplers, and they should be kept free of dirt, rust and moisture. A two-person crew is normally recommended for deep sampling, and depths of 20 m may be sampled (Figure I.4.11). A volume of soil core of at least 100 cm^3 is recommended.

The open-drive sampler consists of a core barrel of 50 mm inside diameter and 100 mm long, with extension tubes of 25 mm in diameter and 1.5 m long for sampling at depth. Brass cylinder liners, 50-mm in length, are used to retain the undisturbed core samples. The samples are removed from the core barrel by pushing a plunger. A light drill rod or 15-mm pipe may be used as extensions.

A simple and economical sampler for obtaining volumetric core samples from shallow depths consists of a thin-walled brass tube 50 mm in diameter and 150 mm long mounted on the end of a 90-cm T-handle of 19-mm pipe. After samplers are removed from the hole, they are pushed out of the core barrel by the central plunger. Since the inside diameter of the core barrel is known, volumetric samples may be obtained easily by cutting off predetermined lengths of the core as it is removed from the sampler.

Laboratory procedure

First, the wet soil samples are weighed individually in their transport containers. The containers are then opened and placed in a drying oven that is capable of maintaining a temperature of 105°C ±0.5. For samples that contain peat or significant

Figure I.4.10. Soil sampling kit
(Source: http://www.colparmer.com/catalog/product_view.asp?sku=9902640)

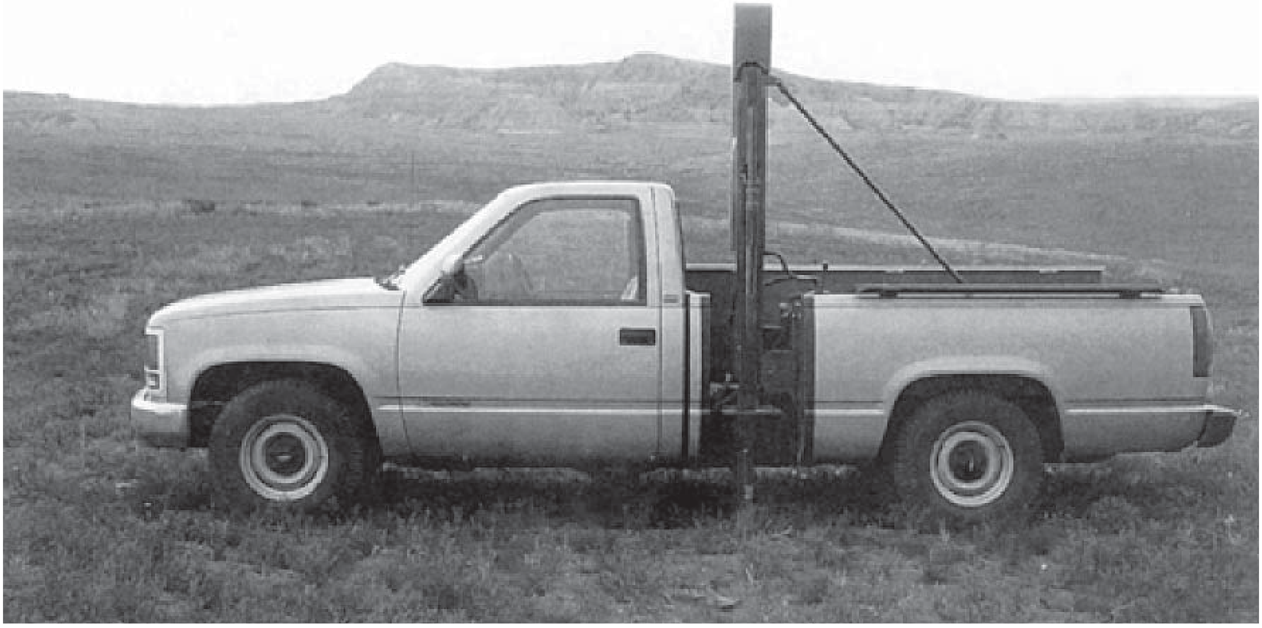


Figure I.4.11. A hydraulically operated sampling tube mounted on a small lorry. The open-faced tube is in place. Hydraulic controls are at the right.

amounts of gypsum, the oven temperature should be 50°C ±0.5, which will then require a longer time for the sample to reach a dry state.

After drying, the samples are reweighed in their containers. The difference in the wet and dry weights for a sample is the measure of its original water content. Other drying processes that are faster than the standard oven may be used, for example, alcohol roasting, infra-red lamps and microwave ovens.

If the samples contain gravel and stones, the above procedure can be modified if the weights or volumes of the gravel and/or stones can be determined separately.

The advantages and disadvantages of the method are given below.

Advantages: This technique is relatively inexpensive, simple and highly accurate.

Disadvantages: This technique is time-consuming, labour-intensive and difficult in rocky soils.

4.5.2.2 **Neutron scatter method** [HOMS C58]

The neutron method indicates the amount of water per unit volume of soil. The soil volume measured by this method is bulb-shaped and has a radius of 1 to 4 m, according to the moisture content and the activity of the source.

This method is based on the principle of measuring the slowing of neutrons emitted into the soil from a fast-neutron source (Greacen, 1981). The energy loss is much greater in neutron collisions with atoms of low atomic weight and is proportional to the number of such atoms present in the soil. The effect of such collisions is to change a fast neutron to a slow neutron. Hydrogen, which is the principal element of low atomic weight found in the soil, is largely contained in the molecules of the water in the soil. The number of slow neutrons detected by a counter tube after emission of fast neutrons from a radioactive source tube is electronically indicated on a scale.

Instruments

A typical set of equipment consists of a portable battery-powered or spring-wound timer that has a time-accounting range of 0.5 to 5 minutes and weighs approximately 16 kg, and a moisture probe containing a 100-mCi fast-neutron source of americium-241 and finely ground beryllium (half-life, 458 years). The probe has a length of about 400 mm, a diameter of about 40 mm and a weight of 20 kg when complete with a lead and paraffin shield that is 150 mm in diameter and 100 mm long (Figure I.4.12). These probes have been used with up to 60 m of cable.

The source and detector are lowered into the soil through a hole cased with aluminium tubing, and readings can be taken at any depth except close to the surface. The inside diameter of the tube should be only slightly larger than the diameter of the probe. The tube should be installed by augering the soil inside the tube, if possible, to ensure close contact between the outside surface of the tube and the soil.

Similar gauges have been developed to make measurements in the surface layers of the soil. In this case, the equipment is placed on the ground surface and gives the moisture content of a hemispherical volume of 15- to 40-cm radius.

Access tubes

The installation of access tubes must be performed carefully to prevent soil compaction and to ensure soil contact around the outside of the tubes, that is, no voids in the soil should be created outside the tubes during their installation. Access tubes may be installed:

(a) By inserting the tubes into prepared holes of the same or slightly smaller diameter (the holes can be prepared by using either a hand-powered or motorized auger);
(b) By driving the tubes into the soil with a hammer and then removing the soil from inside the tubes with an auger.

The bottom ends of the tubes should be sealed to prevent infiltration of groundwater. The top ends of the tubes should be sealed with a cap or a stopper when not in use.

Calibration

The probe should be calibrated by gravimetric sampling (4.5.2.1) of the type of soil that is to be tested and in the size and type of casing into which the probe is to be lowered. Sufficient samples should be taken around the test hole to define the soil moisture profile. It is difficult to obtain a good calibration in heterogeneous soil or when soil moisture is changing rapidly with depth. An approximate calibration can also be carried out in the laboratory by using a container filled with soil material. The type and size of casing and the method of installation of the access tube have a considerable effect on the readings, and new calibration curves should be obtained for each type of installation.

Measurements and accuracy

The access tubes must be kept free of excess moisture or erroneous readings will result.

After lowering the probe to the proper depth in the access tube, the number of counts over a known time period is determined. The average count is converted to soil moisture content by using the calibration curve. The accuracy of a determination depends primarily on:

(a) The validity of the calibration curve;
(b) The number of counts per determination.

Because of the randomness of the emission and the impact of neutrons, random count errors can occur. Timing errors may be kept to a minimum by using a standard-count timing cycle of two minutes.

Salt concentrations in the range ordinarily found in soil moisture do not materially affect data obtained by the neutron method, but at salt concentrations at the level of seawater, the effect is appreciable. There is some evidence of a temperature effect.

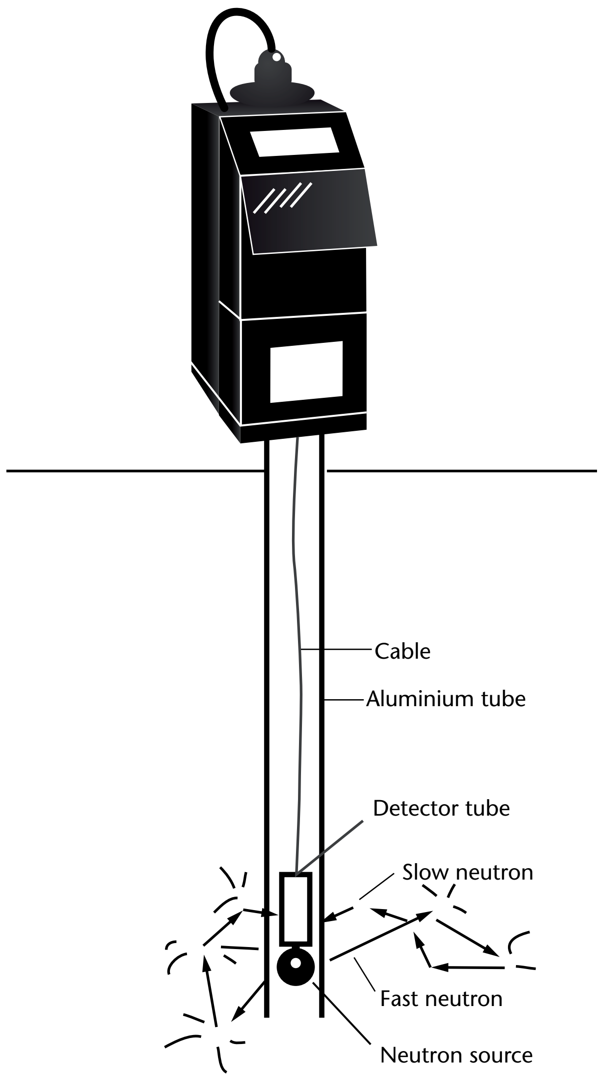


Figure I.4.12. Neutron probe

Readings close to the surface are affected by the position of the probe with respect to the air-soil interface. Proximity of the interface causes lower counts than would be indicated for the same moisture content at a greater depth.

When the error sources are minimized, the accuracy of an individual determination can reach 0.5 to 1 per cent. For repeated determinations over time, such as might be performed in a water-balance study, the changes in water content of soil can be even more accurate because of the elimination of systematic errors.

The advantages and disadvantages of the method and the availability of instruments for its use are summarized below (Prichard, 2003):

Advantages: The neutron probe allows a rapid, accurate, repeatable measurement of soil moisture content to be made at several depths and locations.

Disadvantages: The use of radioactive material requiring a licensed and extensively trained operator, the high equipment cost and extensive calibration required for each site.

Readily available instruments: Neutron probes are available commercially.

4.5.2.3 **Dielectric methods** [HOMS C60]

The dielectric constant methods seek to measure the capacity of a non-conductor (soil) to transmit high-frequency electromagnetic waves or pulses. The resultant values are related through calibration to soil moisture content.

The basis for use of these instruments is that dry soil has dielectric values of about 2 to 5 and that of water is 80 when measured between 30 MHz and 1 GHz.

Two approaches have been developed for measuring the dielectric constant of the soil water media and estimating the soil volumetric water content:
(a) Time domain reflectrometry (TDR);
(b) Frequency domain reflectrometry (FDR).

Neither TDR nor FDR use a radioactive source, thereby reducing the cost of licensing, training and monitoring when compared with the use of the neutron probe.

Time domain reflectrometry

The TDR device propagates a high-frequency transverse electromagnetic wave along a cable attached to a parallel conducting probe inserted into the soil. The signal is reflected from one probe to the other, then back to the meter, which measures the time between sending the pulse and receiving the reflected wave. By knowing the cable length and waveguide length, the propagation velocity can be computed. The faster the propagation velocity, the lower the dielectric constant and thus lower soil moisture.

Waveguides are usually a pair of stainless steel rods, which are inserted into the soil a few centimetres apart. The measurement is the average volumetric water content along the length of the waveguide if so calibrated. Waveguides are installed from the surface to a maximum depth of usually 45–60 cm. Pairs of rods can be permanently installed to provide water content at different depths. If deeper measurements are needed, a pit is usually dug after which the waveguides are inserted into the undisturbed pit wall. The soil disruption can change water movement and water extraction patterns, resulting in erroneous data.

TDR units are relatively expensive. However, once properly calibrated and installed, the TDR technique is highly accurate. Since surface measurements can be made easily and in multiple sites, it works well for shallow rooted crops.

Frequency domain reflectrometry

This approach uses radio frequency waves to measure soil capacitance. The soil acts as the dielectric completing a capacitance circuit, which is part of a feedback loop of a high-frequency transistor oscillator. The frequency varies between instrument manufacturers but is generally about 150 MHz. The soil capacitance is related to the dielectric constant by the geometry of the electric field established around the electrodes. The dielectric constant is then related to the volumetric water content as discussed in the TDR method. Two distinct types of instruments use the FDR techniques – an access tube method and a hand-held push probe.

Access tube type

An access tube of PVC material similar to one being used in the neutron probe and the electrodes is lowered into the access well and measurements are taken at various depths. It is necessary to ensure a very close fit between the walls of the access tube and the soil to ensure reliable values as air gaps affect the travel of the signal in the soil. Calibration to soil volumetric water content is required (especially in clayey soils and those with high bulk densities) to ensure accurate values. If properly calibrated and installed, the accuracy of the probe can be good.

Many of the advantages of the neutron probe are available with this system, including rapid measurements at the same locations and depths over time.

Another variant of this technology is the use of a permanent installation, which reads multiple depths. These are used in conjunction with electronics to make frequent readings and transmit results to a central data-collection device.

Hand-push probe

The other type of capacitance device is a hand-push probe, which allows rapid, easy, near-surface readings. These probes provide a qualitative measurement of soil water content on a scale from 1 to 100 with high readings indicating higher soil moisture content. Probe use in drier soils and those containing stones or hard pans is difficult. Deeper measurements are possible using a soil auger to gain access to deeper parts of the root zone. The probe is best used in shallow-rooted crops.

Advantages: The advantages of the TDR and FDR equipment is that they are relatively accurate (±1–2 per cent); can provide direct readouts of volumetric, available plant soil moisture percentages or continuous readings if used with a data logger; do not require calibration; and are relatively unaffected by salts in the soil. TDR is more accurate and less affected by salts while FDR can detect "bound" water in fine particle soils, which is still available to plants. Thus, the TDR instrument would be preferable for extensive acreage of salt-affected soils. However, if dealing with primarily fine-textured, non-saline soils, the FDR instrument would be preferable. In general, these instruments are accurate, reasonably priced, easy to use and very suitable for large areas.

Disadvantages: Owing to the cost of the instruments, these methods are more expensive than others. Readings can be affected if good contact is not made with the soil, and prongs can be damaged in hard or rocky soils. TDR has complex electronics and is the most expensive, whereas FDR is more susceptible to soil salinity errors. Data logger readings are in the form of graphs requiring interpretation.

4.5.2.4 Gamma-ray attenuation

The intensity of a gamma ray that passes through a soil section undergoes an exponential decrease that principally depends on the apparent density of the soil, the water contained in the soil and the coefficients of attenuation of the soil and of the water, which are constants. The method consists of concurrently lowering a gamma-ray source (generally Caesium 137) and a gamma-ray detector (scintillator-photomultiplier) down a pair of parallel access tubes that have been installed in the soil. At each measurement level, the signal can be translated into the apparent wet density of the soil or, if the apparent dry bulk density of the soil is known, the signal can be converted into a measure of the volumetric soil-moisture content.

The measuring equipment permits tracking of the evolution of wet density profiles and of the volumetric soil-moisture at several tens of centimetres of depth below the soil surface if the dry density does not vary with time.

The method has the advantage of having a high spatial resolution (it measures over a slice of soil 20 to 50 mm in thickness with the access tubes separated by about 3 m). However, the measurements are not specific to water alone. The apparent variations in dry density can confound the measurements of soil moisture.

Some complex equipment has two energy sources with different intensities of gamma rays, which permit the joint study of the variations in both apparent density and soil moisture. Such equipment is used primarily in laboratories and not under field conditions.

4.5.3 Qualitative methods

4.5.3.1 Tensiometric method [HOMS C62]

The components of a tensiometer include the porous cup, the connecting tube and/or the body tube and the pressure sensor. The porous cup is made of a porous, rigid material, usually ceramic. The pores of the cup wall are small enough to prevent the passage of air. A semi-rigid connecting tube and/or a rigid body tube are used to connect the tensiometer cup to the pressure sensor. The system is filled with water and the water in the point or cup comes into equilibrium with the moisture in the surrounding soil. Water flows out of the point as the soil dries and creates greater tension, or flows back into the point as the soil becomes wetter thereby decreasing the tension. These changes in pressure or tension are indicated on the measuring device. Multiple tensiometres located at several depths permit the computation of a soil-moisture profile.

Tensiometers provide data on soil-water potential (pressure components). If a tensiometer is used for moisture determinations, a calibration curve is needed. The calibration curve may be a part of the soil-moisture retention curve, but it is recommended that field data from the gravimetric method (4.5.2.1) and tensiometer readings be used for the calibration. Even so, the moisture data are only approximate, because of the hysteresis between the wetting and drying branches of the soil-moisture retention curve. The range of use is restricted to 0 to 0.8 bars (0 to 8 m of negative hydraulic head). Therefore, the method is suitable only for wet regions.

The pressure measuring device is usually a Bourdon-tube vacuum gauge or a mercury manometer. The tensiometer may also be attached to an electrical pressure transducer to maintain a continuous record of tension changes. Because the system is under a partial vacuum during unsaturated soil conditions, it is necessary that all parts or joints be impermeable to air. For field use, Bourdon vacuum gauges are more convenient than mercury manometers, but they have a lower accuracy. Electrical pressure transducers are both convenient and precise.

The tensiometer response time is much faster with pressure transducers that have small volume displacements than with other pressure sensors. The disadvantage of the cost can be offset by using only one electrical pressure transducer connected to several tensiometers via a scanning device. Another solution consists of using a measuring apparatus that briefly samples the pressure in the tensiometer by means of a needle. This needle perforates a special bulb on the tensiometer tube only during the moment of the measurement. A single needle apparatus can be used to sample numerous tensiometers placed in the soil. However, unlike the system described above, this type of tensiometer cannot be used to record changes of pressure potential.

Tensiometers should be filled with de-aerated water. Then it would be possible to remove air trapped inside the system by using a vacuum pump. Tensiometers are generally inserted vertically into the soil in pre-augered holes of the same diameter as the porous cup. The centre of the porous cup is located at the depth where pressure measurement is required. Tensiometers are affected by temperature fluctuations that induce thermal expansion or contraction of the different parts of the system and that influence the pressure readings. In the field, protection from solar radiation is recommended for tensiometers that are above ground to minimize this influence. Similarly, tensiometers used in the winter should be protected against frost damage to the water tube and the pressure sensor. Tensiometers need to be purged periodically to remove accumulated air from the system.

A tensiometer reading indicates the pressure in the porous cup minus the pressure difference caused by the water column between pressure sensor and porous cup. Therefore, the pressure potential of the soil water at the depth of the cup is the pressure sensor reading plus that of this water column. If the pressure is expressed in terms of suction, that is, atmospheric pressure minus gauge pressure, then the pressure potential of the soil equals the sensor reading minus the pressure difference caused by the water column in the tube. Corrected pressure potential of the soil can be generated directly with pressure transducer systems.

It is difficult to state the precision of a tensiometer measurement of soil-water pressure potential. The accuracy of a measurement is influenced by temperature, the accuracy of the pressure sensor and the quantity of air accumulated within the system. Moreover, the response time of tensiometers can cause erroneous measurements if the soil-water potential is changing quite rapidly in time. In this case, equilibrium between the soil water and the tensiometer water cannot be obtained. Recent studies have shown that semi-permeable plastic points provide much faster response than ceramic points (Klute, 1986).

The tensiometer is probably the easiest to install and the most rapidly read of all soil-moisture measuring equipment. However, tensiometers are not suitable for installation at depths greater than 3 m. At normal atmospheric pressures, the method is limited to a range of pressure potential down to about –85 kPa. Tensiometers require frequent servicing to obtain reliable measurements under field conditions.

Advantages: Tensiometers are not affected by the amount of salts dissolved in the soil water. They measure soil water tension with a reasonable accuracy in the wet range.

Disadvantages: Tensiometers only operate between saturation and about –85 kPa. Thus they are not suited for measurement in dry soils.

4.5.3.2 **Porous blocks/electrical resistance blocks** [HOMS C60]

Porous blocks are made of gypsum, glass/gypsum matrix, ceramic, nylon and fibreglass. They are buried at the depth of measurement desired. Over time, the blocks come to equilibrium with the moisture content in the surrounding soil. Therefore, the subsequent measurement is related to soil water tension.

In the case of electrical resistance blocks, two electrodes are buried inside the block with a cable extending to the surface. The electrical resistance is measured between the two electrodes using a meter attached to the cable. Higher resistance readings mean lower block water content and higher soil water tension.

Porous blocks require the same careful installation as tensiometers and good soil contact is important. Maintenance requirement is small and is much less than for tensiometers. Gypsum blocks are proven to break down in alkaline soils and will eventually dissolve, necessitating an abandonment or replacement. Soils high in soluble salts may cause erroneous readings, as salts influence soil conductivity and resistance. Gypsum blocks are best suited for fine-textured soils, as they are not generally sensitive below 1 000 hPa For most sandy soils, this would be outside the level of available water.

A newer type of gypsum block consists of a fine granular matrix with gypsum compressed into a block containing electrodes. The outside surface of the matrix is incised in a synthetic membrane and is placed in a perforated PVC or stainless steel protective cover. The construction materials enhance water movement to and from the block, making it more responsive to soil water tensions in the 300–2 000 hPa range. This makes them more adaptable to a wider range of soil textures.

Thermal dissipation blocks: These are made of a porous, ceramic material. Embedded inside a porous block is a small heater and temperature sensor attached by cable to a surface meter. A measurement is made by applying voltage to an internal heater and measuring the rate at which heat is conducted away from the heater (heat dissipation). The rate of heat dissipation is related to moisture content.

Thermal dissipation sensors are sensitive to soil water across a wide range of soil water contents; however, to yield water content they must be individually calibrated. These blocks are considerably more expensive than electrical resistance blocks.

Advantages: The method is quick, repeatable and relatively inexpensive.

Disadvantages: The blocks do not work well in coarse-textured, high shrink-swell, or saline soils. Accuracy is rather poor unless blocks are individually calibrated for the soil being monitored using a pressure plate extractor or gravimetric method. Blocks should be replaced every one to three years. Major consideration is that the sensitivity of the blocks is poor in dry soil conditions. The blocks need to be soaked in water for several hours before they are installed in the field.

4.5.4 **Remote-sensing** [HOMS D]

The remote-sensing technique is the most recent tool being used to estimate soil moisture properties at or near the surface. This information may be used to infer soil moisture profiles down to several metres. Remote-sensing of soil moisture can be accomplished using visible, infra-red (near and thermal), microwave and gamma data (Engman and Gurney, 1991; Schultz and Engman, 2000). However, the most promising techniques are based on the passive and active microwave data. The visible and near-infra-red techniques, which are based on the measurement of reflected solar radiation, are not particularly viable because there are too many noise elements that confuse the interpretation of the data. The thermal infra-red techniques are based on the relationship between the diurnal temperature cycle and soil moisture, which depend upon soil type and is largely limited to bare soil conditions. A main problem associated with thermal infra-red techniques is cloud interference. Microwave techniques for measuring soil moisture include both passive and active microwave approaches; each has distinct advantages. Microwave techniques are based on a large contrast between dielectric properties of liquid water and dry soil. The variation of natural terrestrial gamma radiation can be used to measure soil moisture because gamma radiation is strongly attenuated by water. It appears that operational remote-sensing of soil moisture will involve more than one sensor. Furthermore, both active microwave and thermal infra-red applications need much additional research before they can be used to extract soil moisture information.

The reflection from bare soil, in the visible and near-infra-red parts of the electromagnetic spectrum, can only be used under limited conditions to estimate soil moisture. The accuracy of this method is poor and absolute values of soil moisture cannot be obtained. More spectral bands and a much higher geometrical resolution in the (VIS/NIR) infra-red visible/near range are needed for soil moisture and agricultural purposes, than that available from

Landsat, SPOT and the NOAA satellites. Soil moisture has been estimated by using precipitation indices; operational applications have been developed by FAO using geostationary imagery over intertropical regions (WMO, 1993). With the advent of the International Geosphere–Biosphere Programme (IGBP) the need for high-resolution data is increasing.

Thermal infra-red techniques have been successfully used to measure the few surface centimetres of soil moisture. A limitation to the thermal approach is that it cannot effectively be applied to surfaces with vegetation cover.

Attempts have been made to evaluate the soil moisture through observation of the Apparent Thermal Inertia using both AVHRR data from Landsat and SPOT and geostationary images; applications have been more of pilot projects rather than operational (WMO, 1993).

Microwave techniques have shown a lot of potential for measuring soil moisture but still need varying amounts of research to make them operational. In order to progress to operational soil moisture monitoring by remote-sensing techniques, multifrequency and multipolarization satellite data will be required; such data are needed to quantify different surfaces and thus reduce the amount of ground truth required.

Only in the microwave region is there a direct physical relationship between soil moisture and the reflection or emission of radiation. A unique advantage of using the microwave region is that at long wavelengths the soil moisture measurements can be made through clouds. It has also been illustrated that the synergistic use of optical and microwave data in agrometeorological applications is advantageous. The passive microwave region has been exploited the most so far. At present, microwave radiometers capable of measuring soil moisture are available only on aircraft. These are being used in both research and a few operational applications.

Soil moisture information at a depth of several metres can be obtained from short pulse radar (wavelengths of 5–10 cm) techniques. In the Russian Federation, this aircraft-based method is used for soil moisture measurements in forested areas and for detecting zones of saturation down to a depth of 5–10 m. The use of gamma radiation is potentially the most accurate of the remote-sensing methods developed for soil moisture measurement. The attenuation of gamma radiation can be used to determine changes in soil moisture in the top 20–30 cm of the ground. This technique requires that some field measurements of soil moisture be made during the measurement flight, because it does not give the absolute values of soil moisture. (WMO, 1992*b*).

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CHAPTER 5

SURFACE WATER QUANTITY AND SEDIMENT MEASUREMENT

5.1 WATER LEVELS OF RIVERS, LAKES AND RESERVOIRS

5.1.1 General

Water level, or stage, is the elevation of the water surface of a stream, lake or other water body relative to a datum (ISO, 1988*b*), and may be used directly in forecasting flows, to delineate flood hazard areas and to design structures in or near water bodies. When correlated with stream discharge or with the storage volumes of reservoirs and lakes, water levels become the basis for computation of discharge or storage records. An expanded discussion of this topic is given in the *Manual on Stream Gauging* (WMO-No. 519).

The site selected for observation of stage should be governed by the purpose for which the records are collected and by the accessibility of the site. Hydraulic conditions are an important factor in site selection on streams, particularly where water levels are used to compute discharge records. Gauges on lakes and reservoirs are normally located near their outlets, but sufficiently upstream to avoid the influence of drawdown.

5.1.2 Gauges for measurement of stage [HOMS C71]

5.1.2.1 Non-recording gauges

Several types of non-recording gauges for measuring stage are used in hydrometric practice. The common gauges are of the following types:

(a) Graduated vertical staff gauge;
(b) Ramp or inclined gauge;
(c) Wire-weight gauge installed on a structure above the stream;
(d) Graduated rod, tape, wire or point gauge for measuring the distance to the water surface;
(e) Maximum-stage gauge for obtaining the elevation of the flood crest by the adherence of regranulated cork to a graduated staff held in a fixed position with relation to the datum.

5.1.2.2 Recording gauges

Many different types of continuously recording stage gauges are in use. They may be classified according to both mode of actuation and mode of recording.

A commonly used installation consists of a stilling well connected to the stream by pipes and a float in the stilling well connected to a wheel on a recorder by a beaded wire or perforated tape. In high velocity streams, it may be necessary to install static tubes on the end of the intake pipes to avoid drawdown of the water level in the well.

The recorder can either be mechanical or electronic. Recorders with the wheel linked to a pencil or pen and the pencil or pen placed on a strip chart moved by a mechanical clock are still widely used and have proved to be reliable. The timescale and stage scale chosen for a particular station will depend on the range in stage, sensitivity of the stage-discharge relation, and runoff characteristics of the basin. Back in the main office the strip chart can be digitized so that the data can be entered into a computer. The wheel can also be connected directly to an encoder. The encoder will give out analogue or digital values that can be read and stored by a data logger.

Various pressure-actuated recording gauges in common use operate on the principle that static pressure at a fixed point in the stream is directly proportional to the head of liquid above the point. This relation is described by the following equation:

$$\textit{Water level} = (P_{static} - P_{atm})\, C \qquad (5.1)$$

where P_{static} is the pressure in bar on a fixed spot in the water column (one has to make sure that any dynamic pressure from water movement is not measured), P_{atm} is the atmospheric pressure in bar on the surface of the water column, and C is a factor of the water's net weight (C = 10.2 for freshwater at 20°C), which changes with the temperature and salinity of the water. Some gauges use a gas-purge system to transmit the pressure to the gauge. A small quantity of air or inert gas (for example, nitrogen) is allowed to bubble through a pipe or tubing to an orifice in the stream. The pressure of the air or gas that displaces the liquid in the pipe is then measured and recorded. Other gauges use pressure transmitters placed directly into the riverbed.

Compensating for the atmospheric pressure is done by taking air down a small ventilation tube in the cable or by measuring it with another pressure transducer on the surface. The main advantage of pressure-actuated recorders is that they do not require a stilling well, although any unfortunate alignment of the pressure-transducer with respect to flow can cause significant error, and the gas purge systems in particular are not sensitive to sediment if its concentration is in the range normally encountered in a natural setting. Care has to be taken when placing the pressure transducer or bubble gauge on the riverbed. It is important to make sure it does not move and that it is exposed only to static pressure. Compensating for changes in temperature and atmospheric pressure on the surface is also critical.

Two kinds of recording gauge that have come into recent use are those that use ultrasonic or radar sensors. The ultrasonic sensor is based on the speed of transit of a pulse of ultrasonic frequency (>20 kHz), which is emitted by a transmitter located in a structure over the lake or the river. When the pulse hits the surface of the water body, it echoes back to the sensor. The time T which passes from the moment of emission of the pulse and the moment of reception of the echo by the sensor is directly proportional to the distance d between the sensor and the water surface, and inversely proportional to the speed of the pulse in the air. It can be calculated as:

$$T=2d/v \tag{5.2}$$

As sound speed depends on air temperature, it is necessary to compensate with a correction factor to obtain a precise value. The radar sensor is similar to the ultrasonic sensor, but uses high frequencies (around 20 GHz). It has the advantage that at the higher frequency the transit speed of the pulse is not affected by air temperature.

River stage may be recorded on graphical (analogue) recorders. Alternatively the stage can be recorded digitally at fixed or action-triggered intervals.

5.1.3 Procedures for measurement of stage

5.1.3.1 Establishment of gauge datum

To avoid negative readings, the gauge should be set so that a reading of zero is below the lowest anticipated stage. The gauge datum should be checked annually by levelling from local benchmarks. It is important to maintain the same gauge datum throughout the period of record. If feasible, the local gauge datum should be tied to a national or regional datum. The precise locations of the benchmarks should be carefully documented.

5.1.3.2 Recording gauges

The graphical, digital, electronic, or telemetering device recorder is set by reference to an auxiliary tape-float gauge or to a staff gauge located inside the stilling well. In addition, a staff, ramp or wire-weight gauge set to the same datum is necessary to compare the water surface elevation in the stilling well with that of the river. For gauges with gas-purge systems and no stilling well, the staff, ramp or wire-weight gauge in the river should serve as the reference gauge. Small differences usually will occur because of velocity past the ends of the intake pipes. Large differences indicate that the intake pipes may be obstructed.

5.1.3.3 Winter operation of recording gauges

(a) Float-actuated – This type of installation requires a stilling well that must be kept ice-free in winter. This can be done by heating the well with, for example, electricity or gas. Other devices to prevent freezing within a stilling well are a temporary floor within the well at an elevation just below the frost line, and a vertical, open-ended tube, large enough in diameter to receive the float, and containing a layer of fuel oil on the water surface;

(b) Pressure-actuated air bellows and transducers – These types of installations require neither a stilling well nor an operating medium subject to freezing. However, the tube or cable going into water has to be protected from ice.

5.1.4 Frequency of stage measurement

The frequency of recording of water level is determined by the hydrological regime of the water body and by the purposes for collecting the data. At continuous-record gauging stations hourly recordings are normally sufficient for most rivers. For measurement in small or flashy streams and urban catchments, stage has to be recorded more frequently in order to obtain a sufficiently accurate hydrograph. In general, it is recommended to record stage as frequently as possible within the limitations given by the available battery capacity and data memory. Installation of water level recorders is essential for streams where the level is subject to abrupt fluctuations. The non-recording gauge is frequently used as a part of flood forecasting systems, where a local observer is available to report on river stage. For purposes such as flood forecasting or flood management, telemetering systems may be employed to transmit data whenever the stage changes by a predetermined amount.

For some purposes, the recording of only the maximum stages during floods is sufficient and maximum-stage gauges are used. A daily measurement of stage is usually sufficient in lakes and reservoirs for the purpose of computing changes in storage. The recording time interval for a particular station is selected on the basis of the rapidity with which the stage can change and its significance to change in discharge. Flashy streams require shorter time intervals, and large streams allow longer time intervals (ISO, 1981).

Output from pressure transducers, shaft encoders, or other devices that provide electronic outputs representing the stage can also be recorded on electronic data loggers (2.5), or with appropriate interfaces the data can be telemetered from remote locations.

5.2 ICE ON RIVERS, LAKES AND RESERVOIRS

5.2.1 General

Observations of ice conditions on rivers, lakes and reservoirs are of great interest in regions where ice formation affects navigation or results in damage to structures, and where ice jams may form (even to the extent of damming a major river). The obstruction of streamflow by ice can also cause serious local flooding. Long-term data on ice conditions in rivers are extremely valuable in designing various structures, in studying processes of ice formation and dissipation, and in developing methods of ice forecasting.

5.2.2 Elements of ice regime

The most important elements of ice regime to be recorded are the following:
(a) Dates on which flows of floating ice are first observed each winter;
(b) Ratio of the surface area of drifting ice to the open–water surface (ice cover ratio);
(c) Ratio of the surface area of drifting ice to the stationary ice surface;
(d) Dates on which ice becomes immovable;
(e) Thickness of ice;
(f) Features of ice destruction;
(g) Dates of ice break-up;
(h) Dates on which the ice on rivers and reservoirs vanish completely.

5.2.3 Methods of observation

Many of the elements given in 5.2.2 cannot be measured instrumentally and must be evaluated subjectively and recorded in descriptive language. For this reason, it is very important that observers be well trained and that instructions be clearly prepared.

The thickness of ice is measured by means of an auger and a ruler at representative sites. To minimize errors caused by spatial variability in ice thickness, measurements should be made at a minimum of three points spaced over a distance of at least 5 m, and the measurements should be averaged. The depth of any snow on top of the ice should also be measured.

The kilometre signs of navigable rivers or dykes may be used to identify the locations at which ice surveys are routinely conducted. Particularly dangerous conditions (for example, ice jams) must be identified in relation to other landmarks (for example, bridges, river regulation structures and harbours).

Determining some of the characteristics of ice phenomena can be made by means of regular photogrammetric surveys from a location on the shore or by aerial photography. In the case of large rivers, reservoirs or lakes, aircraft observations of ice formation or break-up are of great value. They are also useful in the case of ice gorges when flood warnings are required.

For surveying ice conditions over a reach, a strip width, s, and a flying height, hf, can be determined as a function of focal length, Lf, of the camera being used and the effective width, l, of the film frame, $hf = s\ (Lf/l)$. Because Lf is a camera constant that is approximately equal to 1.0, the strip width is approximately equal to the flying height. By repeat aerial photography at intervals of a few minutes, the velocity of the ice drift can be determined along with the density of cover. If the average ice thickness is known, the ice discharge (throughput) can also be calculated.

Television and IR remote-sensing data from meteorological and Earth-resource satellites are also useful for estimating ice conditions on lakes and reservoirs (Prokacheva, 1975).

5.2.4 Times and frequency of observations

Observations of the state of the ice are made at times when the water level is observed, while ice thickness and snow depth on major rivers, lakes and reservoirs should be measured at intervals of 5 to 10 days during the critical periods of ice formation and break up. Aircraft observations should be made, as required, to meet special purposes.

5.2.5 Accuracy of measurement

The measurement of ice cannot be very accurate because of difficult conditions. However, uncertainty of ice thickness measurement should not exceed 10 to 20 mm or 5 per cent, whichever is greater.

5.3 DISCHARGE MEASUREMENTS AND COMPUTATION

5.3.1 General [HOMS E70]

River discharge, which is expressed as volume per unit time, is the rate at which water flows through a cross-section. Discharge at a given time can be measured by several different methods, and the choice of methods depends on the conditions encountered at a particular site. Normally, the discharge shall be related to a corresponding water stage at a gauging station.

The accuracy of the discharge measurement depends on the length of time required to make the measurement, and the extent to which the stage and the discharge change during the measurement. Changes in the downstream conditions during the measurement can influence the result and should be avoided.

5.3.2 Measurement of discharge by current meters [HOMS C79, C85, C86, C88, E79]

Measurement of discharge by the velocity-area method is explained by reference to Figure I.5.1. The depth of flow in the cross-section is measured at verticals with a rod or sounding line. As the depth is measured, observations of velocity are obtained with a current meter at one or more points in the vertical. The measured widths, depths and velocities permit computation of discharge for each segment of the cross-section. The summation of these segment discharges is the total discharge (ISO, 1979*b*).

5.3.2.1 Selection of site

Discharge measurements need not be made at the exact location of the stage gauge because the discharge is normally the same throughout a reach of channel in the general vicinity of the gauge. Sites selected for measurements should ideally have the following characteristics (ISO, 1979*b*):

(a) The velocities at all points are parallel to one another and at right angles to the cross-section of the stream;
(b) The curves of distribution of velocity in the section are regular in the vertical and horizontal planes;

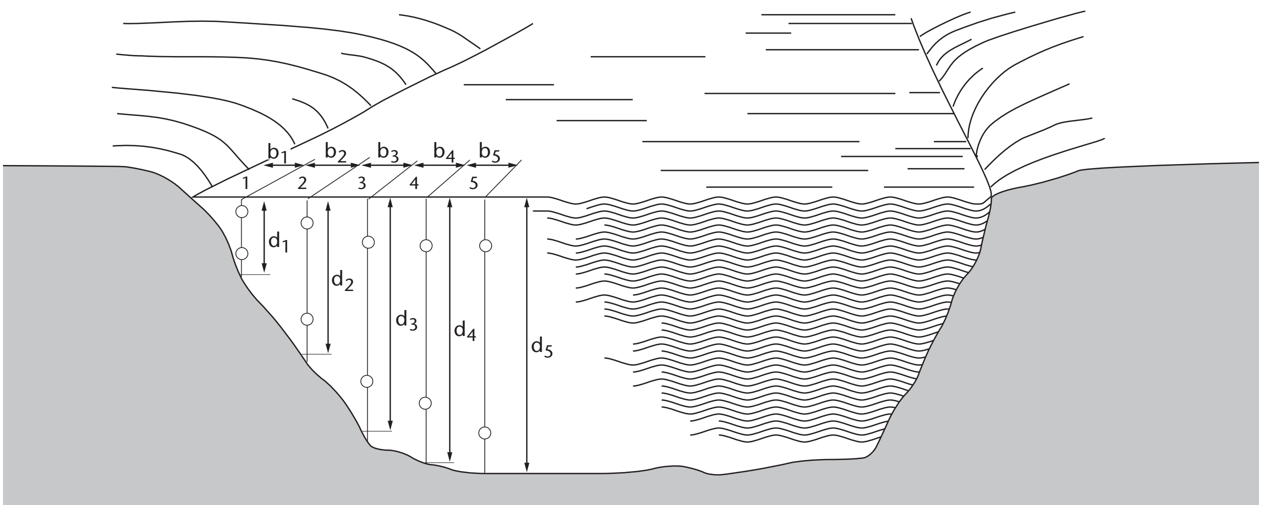

Figure I.5.1. View of a stream cross-section showing the location of points of observation

(c) The velocities are greater than 0.150 m s^{-1};
(d) The bed of the channel is regular and stable;
(e) The depth of flow is greater than 0.300 m;
(f) There is no aquatic growth;
(g) There is minimal formation of slush or frazil ice (5.3.2.5.1).

5.3.2.2 Measurement of cross-section

The accuracy of a discharge measurement depends on the number of verticals at which observations of depth and velocity are obtained. Observation verticals should be located to best define the variation in elevation of the stream bed and the horizontal variation in velocity. In general, the interval between any two verticals should not be greater than 1/20 of the total width and the discharge of any segment should not be more than 10 per cent of the total discharge.

Channel width and the distance between verticals should be obtained by measuring from a fixed reference point (usually an initial point on the bank), which should be in the same plane as the cross-section. Normally, the distance between verticals is determined from graduated tape or beaded wire temporarily stretched across the stream or from semi-permanent marks, for example, painted on a bridge handrail or a suspension cable (ISO, 1979*b*). For large rivers, telemetry systems or triangulation practices can be used for measuring widths.

Depth may be read directly on a graduated rod set on the stream bed if measurement is by wading. If the drum-wire-weight system is used for measurement, the current meter and weight are lowered until the bottom of the weight just touches the water surface, and the depth dial reading is set at zero. The weight is then lowered until it rests on the stream bed, and the depth is read on the dial.

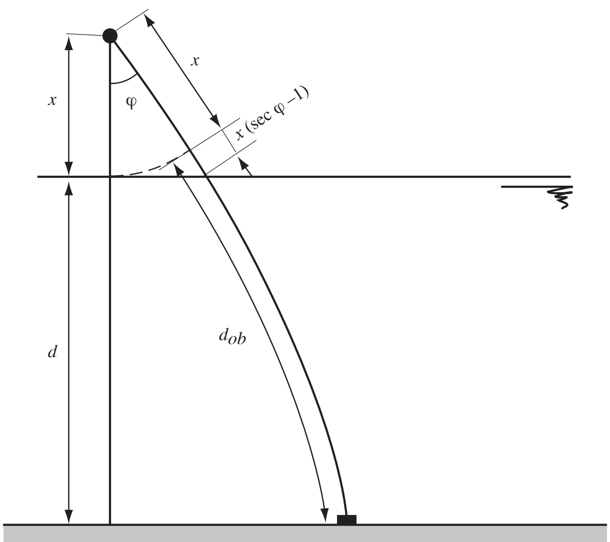

Figure I.5.2. Relationship between correct depth *d* and observed depth d_{ob}

Table I.5.1. Correction factor *k* for given values φ

φ	*k*	φ	*k*	φ	*k*
4°	0.0006	14°	0.0098	24°	0.0256
6°	0.0016	16°	0.0128	26°	0.0350
8°	0.0032	18°	0.0164	28°	0.0408
10°	0.0050	20°	0.0204	30°	0.0472
12°	0.0072	22°	0.0248		

If the weight on the sounding line is not sufficient to keep the line perpendicular to the water surface, the angle between the line and the vertical should be measured to the nearest degree with a protractor. The relationship between the correct depth, *d*, and the observed depth, d_{ob}, based on the observed angle, φ, and the distance from the water surface to the point of suspension of the sounding line, *x*, is shown in Figure I.5.2 and is given below:

$$d = [d_{ob} - x\ (\sec\varphi - l)][1 - k] \tag{5.3}$$

Values of *k* as given in Table I.5.1 are based on the assumptions that the drag pressure on the weight in the comparatively still water near the bottom can be neglected and that the sounding wire and weight are designed to offer little resistance to the water current. The uncertainties in this estimation are such that significant errors may be introduced if the vertical angle is more than 30°.

5.3.2.3 Measurement of velocity [HOMS C79, E79]

5.3.2.3.1 *Meters for measurement of velocity*

Velocity of flow at a point is usually measured by counting revolutions of a current meter rotor during a short-time period measured with a stopwatch (ISO, 1979*b*). Two types of current meter rotors are in general use: the cup type with a vertical shaft and the propeller type with a horizontal shaft. Both types use a make-and-break contact to generate an electric pulse for indicating the revolutions of the rotor (ISO, 1988*a*). Optical, non-contact type counters are also in use with cup-type meters.

Current meters are calibrated to cover the range in velocity of flow to be measured. Detailed calibration procedures are described in ISO 3455 (ISO, 1976). Current meters may be calibrated individually or a group rating may be used. Individually calibrated meters should be recalibrated after three years or 300 hours of use or if their performance is suspect (*Technical Regulations* (WMO-No. 49), Volume III, Annex).

5.3.2.3.2 *Measurement of velocity using the current meter*

Velocity is observed at one or more points in each vertical by counting revolutions of the rotor during a period of not less than 30 seconds. Where the velocity is subject to large periodic pulsations the exposure time should be increased accordingly (*Technical Regulations* (WMO-No. 49), Volume III, Annex).

For shallow channels, the current meter should be held in the desired position by means of a wading rod. For channels too deep or swift to wade, it should be positioned by suspending it from a wire or rod from a bridge, cableway or boat. When a boat is used, the meter should be held so that it is not affected by disturbances to the natural flow caused by the boat. After the meter has been placed at the selected point in the vertical, it should be allowed to become aligned with the direction of flow before readings are started. If oblique flow is unavoidable, the angle of the direction of the flow normal to the cross-section should be measured and the measured velocity should be corrected. If the measured angle to the normal is γ, then:

$$V_{normal} = V_{measured} \cos \gamma \tag{5.4}$$

The meter on cable suspension will automatically point in the direction of the current owing to the tail vanes built into the meter. In some cases, such as using an oblique bridge as the measuring section, the horizontal distances should be corrected as:

$$d_{normal} = d_{measured} \cos \gamma \tag{5.5}$$

The current meter should be removed from the water at intervals for examination. For measuring very low velocities, special current meters may be used if they have been tested in this range of velocities for repeatability and accuracy.

The horizontal axis of the current meter should not be situated at a distance less than one and one-half times the rotor height from the water surface, nor should it be at a distance less than three times the rotor height from the bottom of the channel. Furthermore, no part of the meter should break the surface of the water (*Technical Regulations* (WMO-No. 49), Volume III, Annex).

5.3.2.3.3 *Determination of mean velocity in a vertical*

The mean velocity of the water in each vertical can be determined by one of the following methods:
(a) Velocity distribution method;
(b) Reduced point methods;
(c) Integration method.

Selection of the appropriate method depends on the time available, the width and depth of the water, the bed conditions, the rate of change of stage, the velocity of the water, the existence of ice cover and the required accuracy.

Velocity distribution method

The measurement of the mean velocity by this method is obtained from velocity observations made at a number of points along each vertical between the surface of the water and the bed of the channel. The velocity observations at each position should be plotted in graphical form and the mean velocity should be determined by dividing the area of this plot by the depth. In developing the graph it may be necessary to estimate the velocities near the stream bed by assuming that the velocity for some distance up from the bed of the channel is proportional to the logarithm of the distance x from that boundary. If the observed velocity at points approaching the bed are plotted against log x, then the best-fitting straight line through these points can be extended to the bed and the velocities close to the bed read from this graph.

The velocity distribution method may not be suitable for discharge measurements made during significant variations of stage because the apparent gain in precision may be more than offset by errors resulting from the longer period required to make the measurement.

The velocity distribution method is valuable in determining coefficients for application to the results obtained by other methods, but it is not generally adapted to routine discharge measurements because of the extra time to compute the mean velocity.

Reduced point methods

(a) One-point method – Velocity observations should be made at each vertical by placing the current meter at 0.6 of the depth below the surface. The value observed should be taken as the mean velocity in the vertical. Where measurements are made under ice cover, this method is applicable with a correction factor of 0.92 for depths shallower than 1 m. Under ice conditions, the current meter may be placed at 0.5 of the depth. A correction factor of 0.88 is then applied to this result;

(b) Two-point method – Velocity observations should be made at each vertical by placing the current meter at 0.2 and 0.8 of the depth below the surface. The average of the two values should be taken as the mean velocity in the vertical;

(c) Three-point method – Velocity observations are made by placing the current meter at each vertical at 0.2, 0.6 and 0.8 of the depth below the surface. The average of the three values may be taken as the mean velocity in the vertical. Alternatively, the 0.6 measurement may be weighted and the mean velocity may be obtained from the equation:

$$\bar{v} = 0.25\ (v_{0.2} + 2v_{0.6} + v_{0.8}) \qquad (5.6)$$

(d) Five-point method – It consists of velocity measurements on each vertical at 0.2, 0.6 and 0.8 of the depth below the surface and as near as possible to the surface and the bottom. The mean velocity may be determined from a graphical plot of the velocity profile as with the velocity distribution method or from the equation:

$$\bar{v} = 0.1\ (v_{surface} + 3v_{0.2} + 3v_{0.6} + 2v_{0.8} + v_{bed}) \qquad (5.7)$$

(e) Six-point method – Velocity observations are made by placing the current meter at 0.2, 0.4, 0.6 and 0.8 of the depth below the surface and as near as possible to the surface and the bottom. The velocity observations are plotted in graphical form and the mean velocity is determined as with the velocity distribution method or from the equation:

$$\bar{v} = 0.1\ (v_{surface} + 2v_{0.2} + 2v_{0.4} + 2v_{0.6} + 2v_{0.8} + v_{bed}) \qquad (5.8)$$

(f) Two-tenths method – In this method, the velocity is observed at 0.2 of the depth below the surface. A coefficient of about 0.88 is applied to the observed velocity to obtain the mean in the vertical;

(g) Surface velocity method – In this method, velocity observations are made as near as possible to the surface. A surface coefficient of 0.85 or 0.86 is used to compute the mean velocity in the vertical.

The two-point method is used where the velocity distribution is normal and depth is greater than about 60 cm. The one-point method is used for shallower depths. The three-point method should be used for measurements under ice or in stream channels overgrown by aquatic vegetation. The five-point method is used where the vertical distribution of velocity is very irregular. The six-point method may be used in difficult conditions, where, for instance, there is aquatic growth, or there is a covering ice. Also it can be used where the vertical distribution of velocity is very irregular. The two-tenths method is principally used when it is not possible to position the meter at the 0.8 or 0.6 of the depth. The surface velocity method may be used for measuring flows of such high velocity that is not possible to obtain depth soundings. In this case a general knowledge of the cross-section at the site or a cross-section measured as soon as possible can be used to obtain the depths.

The accuracy of a particular method should be determined, if possible, by observing the velocity at 6 to 10 points in each vertical for the first few discharge measurements made at a new site.

Integration method

In this method, the current meter is lowered and raised through the entire depth at each vertical at a uniform rate. The speed at which the meter is lowered or raised should not be more than 5 per cent of the mean velocity of flow in the cross-section, and it should be between 0.04 and 0.10 m s^{-1}. The average number of revolutions per second is determined. Two complete cycles are made in each vertical and, if the results differ by more than 10 per cent, the measurement is repeated. This method is seldom used in water having a depth of less than 3 m and velocities of less than 1 m s^{-1}. The integration method should not be used with a vertical axis current meter because the vertical movement of the meter affects the motion of the rotor.

5.3.2.4 Computations of discharge

Arithmetical methods

(a) Mean-section method – The cross-section is regarded as being made up of a number of segments bounded by two adjacent verticals. If $\bar{v}_1$ is the mean velocity at the first vertical and $\bar{v}_2$ the mean velocity at the second vertical, and if d_1 and d_2 are the total depths measured at verticals 1 and 2, and b is the horizontal distance between verticals, then the discharge q of the segment is:

$$q = \left(\frac{\bar{v}_1 + \bar{v}_2}{2}\right)\left(\frac{d_1 + d_2}{2}\right) b \quad (5.9)$$

The total discharge is obtained by adding the discharge from each segment;

(b) Mid-section method – The discharge in each segment is computed by multiplying vd in each vertical by a width, which is the sum of half the distances to adjacent verticals. The value of d in the two half-widths next to the banks can be estimated. Referring to Figure I.5.1, the total discharge Q is computed as:

$$Q = \bar{v}_1 d_1 \left(\frac{b_2 + b_1}{2}\right) + \bar{v}_2 d_2 \left(\frac{b_1 + b_2}{2}\right) + \ldots + \bar{v}_n d_n \left(\frac{b_n + b_{n-1}}{2}\right) \quad (5.10)$$

Graphical methods

(a) Depth-velocity integration method – The first step consists in drawing, for each vertical, the depth velocity curve, the area of which represents the product of the mean velocity and the total depth. The value of this product at each vertical is then plotted versus lateral distance and a curve is drawn through the points. The area defined by this curve is the discharge in the cross-section;

(b) Velocity-contour method – Based on the velocity-distribution curves of the verticals, a velocity distribution diagram for the cross-section is prepared showing curves of equal velocity. Starting with the maximum, areas enclosed by the equal velocity curves and the water surface should be measured and then plotted in another diagram, with the ordinate indicating the velocity and the abscissa indicating the area. The area enclosed by the velocity area curve represents the discharge of the cross-section (ISO, 1979*b*).

5.3.2.5 Measurement of discharge under ice cover

Measurement of discharge under ice cover requires general knowledge of instruments and procedures described in 5.3.2.1 to 5.3.2.4. These sections deal only with equipment and procedures peculiar to the measurement of discharge under ice cover.

5.3.2.5.1 *Selection of site*

It is advisable to select alternate cross-sections during the open water season when channel conditions can be evaluated. At some stations, the same measuring section may be used during winter and summer, but it is more important that winter measurements be made under suitable conditions than it is to use the same measuring section. After initial selection, exploratory holes may be cut at quarter points along the section to detect the presence of slush ice or poor distribution of flow. Frazil ice should be avoided whenever possible because ice particles impede the operation of the meter and because of difficulty in determining ice thickness. Also, a small flow may occur through the frazil ice which cannot be measured by usual methods.

Winter freshets often lead to water breaking through the ice and forming two independent currents, one above and the other below the ice. Such locations should be avoided.

5.3.2.5.2 *Equipment*

(a) Cutting holes – When ice is thick, a mechanical ice auger, drill or chainsaw is desirable for cutting holes. For thin ice, an ice chisel may be used;

(b) Determination of effective depth – Effective depth of water below ice cover is the total depth of water minus the distance from the water surface to the underside of the ice. The distance between the water surface in the ice hole and the underside of the ice may be measured using an ice-measuring stick or “ice stick”, which is an L-shaped graduated bar of appropriate length. The short projection of the L-shaped stick is held against the underside of the ice, and the depth to that point is read at the ice surface on the graduated portion of the stick. If there is slush under solid ice at a hole, the depth at which it ends may be determined by suspending the current meter below the slush ice with the meter rotor turning freely and then raising it slowly until the rotor stops. This point is assumed to be the interface between water and slush;

(c) Current meter and weight assembly – If an ice auger or drill is used to cut holes through ice, a special current meter and sounding weight assembly is passed through the ice hole, which is generally about 150 mm in diameter. The assembly may consist of two teardrop-shaped lead weights, one above and one below the meter, or one teardrop-shaped weight below the meter. When the hole can be made large enough, the standard current meter and weight assembly can be used as described in 5.3.2.3.1;

(d) Meter suspension – The meter suspension may be by a rod, handline or sounding reel. If the total depth of water under ice cover is greater than 3 or 4 m, a reel or handline is usually used. The reel is mounted on a collapsible support set on runners. In extremely cold weather, the support may be equipped with a heated water tank or hot air chamber to keep the meter from freezing while moving the equipment from one position to the next. For shallower depths, where a meter without tail vanes is suspended by a rod through a drilled hole, the direction of current must be determined so that the meter can be properly aligned.

5.3.2.5.3 *Discharge measurement*

(a) Spacing of verticals – The information in 5.3.2.2 is also applicable to the spacing of verticals under ice. However, in addition to the variation in elevation of the stream bed, variation in ice cover and slush ice thickness must also be taken into account in selecting the number and location of verticals. If the current is divided into different channels by slush ice, not less than three verticals should be used in each channel;

(b) Measurement of velocity – Ideally, velocity curves should be determined from velocity observations at every tenth of the effective depth in at least two verticals to determine what coefficients, if any, are necessary to convert the average velocity obtained by any standard open-water method of observation to an average velocity in a vertical under the ice cover. In shallow water, velocity may be observed at one point at either 0.5 or 0.6 of the effective depth, but a coefficient is normally required to convert the observed velocity to mean velocity. In deeper water (1 m or more), velocity observations could include two observations at 0.2 and 0.8 of the effective depth, three observations at 0.15, 0.5 and 0.85 of the effective depth, six observations at 0.2, 0.4, 0.6 and 0.8 of the effective depth, and at points close to the top and bottom. The average velocity observed in the two- and three-point methods may be used as the mean in the vertical. For the six-point method, see 5.3.2.3.3;

(c) General notes – When measuring discharge from an ice cover, appropriate safety precautions should be observed. For example, the safety of ice should always be tested by probing ahead with an ice chisel while moving across the ice. If the velocity measured under ice conditions is less than the accepted lower limit of the current meter, the cross-section should be moved to another reach of the river where the velocity is higher. Care must be taken to ensure that the meter is rotating freely and is not impeded by ice that can accumulate on the meter and freeze while moving from one vertical to another. At the time the measurements are taken, a record should be kept of a complete description of weather and ice conditions on the river, particularly at the control sections. This will aid in the later computation of discharge between measurements.

5.3.2.5.4 *Computation of discharge*

The computation of discharge under ice cover is the same as for open-water conditions described in 5.3.2.4 except that effective depth is used instead of total depth of water.

5.3.2.6 Accuracy of measurement

The accuracy of discharge measurements depends on the reliability of the meter rating, on the conditions of flow, on the skill of the hydrometrist, and on the number of observations of depth and velocity obtained (ISO, 1981; 1985). Measurements are normally made by observing the depth and the velocity at two points, in 20 to 25 verticals in the cross-section. For this type of measurement, under the flow conditions that are usually encountered, the standard error at the 95 per cent confidence level is about 5 per cent (ISO, 1979*b*).

5.3.3 Measurement of discharge by the float method [HOMS C86]

This method should be used in the following instances: it is impossible to use a current meter because of unsuitable velocities or depths, or where there is the presence of a large amount of material in suspension, or when a discharge measurement must be made in a very short time.

5.3.3.1 Selection of sections

Three cross-sections should be selected along a reach of straight channel. The cross-sections should be spaced far enough apart for the time that the float takes to pass from one cross-section to the next to be measured accurately. A travel time of 20 seconds is recommended, but a shorter time may have to be used on small rivers with high velocities where it is often impossible to select an adequate length of straight channel.

5.3.3.2 Floats

Surface floats or rod floats may be used. A surface float has a depth of immersion of less than one quarter the depth of the water. Surface floats should not be used when they are likely to be affected by wind. A rod float has a depth of immersion exceeding one quarter the depth of the water. Rod floats must not touch the channel bed. Floating trees or ice cakes may serve as natural floats during periods when it is unsafe to be on the river.

5.3.3.3 Measuring procedure

Float observations must be uniformly distributed over the width of the stream. The float should be released far enough above the upper cross-section to attain a constant velocity before reaching the first cross-section. The time at which the float crosses each of the three cross-sections should be noted with a stopwatch. This procedure should be repeated with the floats at several locations across the stream. The width of the channel should be divided into segments of equal width or of approximately equal discharge. The number of segments should be not less than three, but where possible a minimum of five should be used. Distances of the float from the bank as it passes each cross-section may be determined by suitable optical means, for example, a theodolite.

The depth of flow at points in the cross-section may be determined by surveying methods.

5.3.3.4 Computation of velocity

The velocity of the float is equal to the distance between cross-sections divided by the time of travel. At least five values of the float velocity should be taken at each segment and the mean of these values should be multiplied by a coefficient to obtain the mean water velocity for each segment. This coefficient is based on the shape of the vertical velocity profile and the relative depth of immersion of the float. The coefficient to be applied to the measured velocity should be determined, if possible, for each site by an analysis of discharge measurements that have been made by current meter. When such measurements are not available, an adjustment factor, *F*, from Table I.5.2 may be used for rough estimation.

Alternatively the float velocity may be plotted as a function of the corresponding distance from the bank, and the mean surface velocity across the river should be determined from this plot. The mean velocity of flow in the cross-section is equal to the mean surface velocity multiplied by a coefficient, *K*, the value of which is deduced, if possible, from preceding measurements made with a current meter for smaller discharges.

Table I.5.2. Float velocity adjustment factor *F* as a function of *R*, the ratio of the immersed depth of float to depth of water

R	*F*
0.10 or less	0.86
0.25	0.88
0.50	0.90
0.75	0.94
0.95	0.98

5.3.3.5 Computation of discharge

Discharge in each segment is computed by multiplying the average area of the cross-section of the segment by the mean velocity of flow in the segment. The total discharge is the sum of these discharges (ISO, 1979*b*).

5.3.4 Measurement of discharge by dilution methods [HOMS E73]

The measurement of discharge by this method depends on determining the degree of dilution by the flowing water of an added tracer solution. The method is recommended for sites with excessive turbulence flows. The two principal tracer methods used for discharge measurements are the constant-rate-injection method and the sudden-injection method. The general requirements (5.3.4.1) for both methods are the same (ISO, 1973*a*; 1987).

The dilution method is a fully acceptable method for discharge measurement at sites where the conditions for this method are good.

5.3.4.1 General requirements

A solution of a stable tracer is injected into the stream at either a constant rate or all at once. Computation of the stream discharge requires knowledge of the following factors:

(a) The rate of injection for the constant-rate-injection method or the total amount injected for the sudden-injection method;
(b) The concentration of the tracer in the injected solution;
(c) The calibrated relationship between tracer concentration and the recorded property (for example, conductivity, colour and radioactivity) at the measuring site after it has been well mixed laterally.

The accuracy of these methods critically depends upon:

(a) Adequate mixing of the injected solution throughout the stream cross-section at the sampling section. If the tracer solution is continuously injected, the concentration of the tracer should be essentially constant throughout the sampled section. If the tracer is injected all at once, $\int_0^T c\,dt$ should essentially be the same at all points in the section, where c is the concentration and T is the time for all of the tracer to pass a particular point in the section;

(b) No absorption or adsorption of the added tracer by stream bottom materials, sediments, plants or organisms, and no decomposition of the added tracer in the stream water. The concentration should be determined at the sampling section and at least one other cross-section downstream to verify that there is not a systematic difference in the mean concentration from one sampling section to another.

5.3.4.2 Selection of site

The primary criterion for the selection of sites for measurement of discharge by dilution is adequate mixing of the injected solution with the stream water in a short length of channel. Mixing is enhanced by high boundary roughness and features that cause the channel flow to be highly turbulent, such as at waterfalls, bends or abrupt constrictions. A small injection of rhodamine dye or fluorescein can help to assess the mixing condition at the measuring site. Large dead-water zones between the injection site and the sampling site will often affect the mixing so that the tracer will not be adequately mixed in the cross-section at the sampling site.

5.3.4.3 Tracers and detection equipment

Any substance may be used as a tracer if:

(a) It dissolves readily in the stream's water at ordinary temperatures;

(b) It is absent in the water of the stream or is present only in negligible quantities;

(c) It is not decomposed in the stream's water and is not retained or absorbed by sediment, plants or organisms;

(d) Its concentration can be measured accurately by simple methods;

(e) It is harmless to humans, animals and vegetation in the concentration it assumes in the stream.

The cheapest tracer is common salt. Where the tracer is instantaneously injected into the stream, the required quantity is not particularly large and detection by conductivity methods is relatively simple.

Sodium dichromate is used extensively in the dilution method. Its solubility in water is relatively high (600 kg m^{-3}), and the salt satisfies most requirements of 5.3.4.1. Colourimetric analysis (ISO, 1987) permits the measurement of very low concentrations of sodium dichromate.

Lithium chloride has solubility in water of 600 kg m^{-3} and its concentrations down to 10^{-4} kg m^{-3} can be detected using flame photometric analysis.

Other chemicals used for dilution gauging are sodium iodide, sodium nitrite and manganese sulphate.

Rhodamine WT dye is widely used in the United States in the dilution method. Its absorptive characteristics are much better than those of other rhodamine dyes. The concentration of the dye can be measured using commercially available fluorometers that can measure concentrations of 5 to 10 parts per billion.

Radioactive elements such as bromine-82, gold-198, iodine-131 and sodium-24 have been used as tracers. Concentrations of these elements as low as 10^{-9} may be determined accurately with a counter or count rate meter with the sensing probe suspended in the stream or in a standard counting tank. Although radioactive elements are ideal tracers for the dilution method, the health hazards may limit their use in measurement of stream discharge in some localities.

5.3.4.4 Computation of discharge

Equations used to compute the stream discharge, Q, are based on the principle of continuity of the tracer:

$$Q = \frac{Q_{tr} c_i}{c_s} \qquad \textit{(continuous injection)} \tag{5.11}$$

and

$$Q = \frac{c_i V}{\int_0^\infty c_s\,dt} \qquad \textit{(sudden injection)} \tag{5.12}$$

where Q_{tr} is the rate of injection, c_i is the concentration of injection solution, c_s is the concentration in the stream at the sampling section, V is the volume of injected solution and t is time.

5.3.5 **Computations of discharge by indirect methods** [HOMS E70]

5.2.5.1 General

During flood periods, it may be impossible to measure discharge directly because of the excessive rate of change of discharge, excessive velocities, debris, depths or widths, or because flooded conditions make roads impassable or measuring structures inaccessible. When such conditions occur, the peak discharge may be determined after the flood has subsided by computations that combine well-established hydraulic principles with field observations of channel conditions and flood profiles. All the methods involve the simultaneous solution of continuity of mass and energy equations. Such computations may be made for reaches of river channel, through roadway culverts and bridge openings, and over dams and highway embankments. Although the hydraulic formulae differ for each type of waterway, all the methods involve the following factors:
(a) Geometry and physical characteristics of the channel and boundary conditions of the reach used;
(b) Water-surface elevations at time of peak stage to define the cross-sectional areas and the head difference between two significant points;
(c) Hydraulic factors, such as roughness coefficients based on physical characteristics.

5.3.5.2 Field survey

A reconnaissance study, from maps, by air or by travel in the region, is made to select the most favourable site for determining discharge by one of the indirect methods. The site should be as close as possible to the desired measuring point, and large intervening tributaries or diversions should be avoided. The site must contain good high-water marks defining the water-surface profile during the peak.

A detailed survey is made to define channel geometry adjacent to and within the selected reach, the channel cross-sections, the dimensions and details of culverts, bridges, dams, roadways or other artificial structures, and the positions and locations of high-water marks left by the flood. All factors that affect channel roughness are noted and roughness coefficients are selected. Photographs should be taken of the cross-sections and reach to facilitate office evaluations of site conditions.

From the field survey notes, drawings are made showing the plan, the profiles of the channel bottom and high-water surface on both banks, the cross-sectional areas and details of any artificial structures. Computations are made of hydraulic factors and the discharge is computed.

5.3.5.3 Slope-area measurements

Slope-area measurements require a reach of river channel that is selected for uniformity or uniform variation in hydraulic properties (ISO, 1973*b*). Discharge is computed on the basis of a uniform flow equation, such as the Manning equation, involving channel characteristics, water-surface profiles and roughness coefficients.

5.3.5.4 Measurement of flow through culverts

Peak discharge through culverts can be determined from high-water marks that define the headwater and tailwater elevations, culvert geometry and slopes, and cross-sections that define approach conditions. The head-discharge relationships of culverts have been defined by laboratory investigations and field verification. Peak discharge is determined by the application of continuity and energy equations between the approach section and a section within the culvert barrel. For convenience in computation, culvert flow has been classified into six types on the basis of the location of the control section and the relative heights of the headwater and tailwater elevations.

5.3.5.5 Measurement of flow through width contractions

The contraction of a stream channel by a roadway crossing creates an abrupt drop in water surface elevation between an approach section and the contracted section under the bridge. The contracted section formed by bridge abutments and the channel bed may be used as a discharge control to compute flood flows. The head on the contracted section is defined by high-water marks (upstream and downstream), and the geometry of the channel and bridge is defined by field surveys. The discharge equation results from a combination of the energy and continuity equations for the reach between these two sections.

5.3.5.6 Measurement of flow over weirs, dams and highway embankments

A weir, dam or embankment generally forms a control section at which the discharge may be related to the upstream water-surface elevation. The peak discharge at the control section can be determined on the basis of a field survey of high-water marks and the geometry of the structure. The methods are derived from laboratory and field studies of the discharge characteristics of weirs, dams and embankments.

The fieldwork consists of a survey of headwater and tailwater elevations from high-water marks, an approach cross-section to define velocity of approach, and an exact determination of the profile of the control structure to assign the proper discharge coefficient. Coefficients are available for:
(a) Thin-plated weirs, either discharging freely or submerged;
(b) Broad-crested weirs, not submerged;
(c) Ogee or design-head dams, submerged or not submerged;
(d) Many irregular shapes.

5.3.6 Measurement of discharge under difficult conditions

General discussion on the measurement of discharge under difficult conditions is provided in the *Level and Discharge Measurements under Difficult Conditions* (WMO-No. 650).

5.3.6.1 Unstable channels

Channel instability is characterized by systematic shifts of the bed, high silt content and the presence of various kinds of debris in the flow. Channel instability is a hindrance to the operation of a permanent gauging structure and/or measurement section. This problem can be minimized by selecting a site midway along a straight reach of the river with a uniform section remote from various obstructions (bridges, etc.). The greatest stability in the banks is usually found at places where the channel narrows. On small rivers, the site should be convenient for the construction of a permanent measurement section.

On small streams, where there is no transport of large stones and debris, portable or permanently installed flumes may be used to measure flow. On small rivers, it is desirable, in some cases, to have an artificial section for measurements to improve the stage-discharge relationship. Improvements may take the form of a low weir or flume depending on the specific conditions at the site. The structure should be high enough to remove variable backwater from downstream but not so high as to cause excessive disturbances downstream. At low water, the structure should provide a sensitive relationship between discharges and water levels. To clean the crests of large structures and to provide a means for making current-meter measurements, a footbridge may be provided. Because of the large silt content of unstable channels, it is desirable to use current meters with a sealed contact chamber. Sounding rods should be provided with a foot to prevent them from sinking into the silt.

When measuring discharge by the velocity-area method, the depth is usually determined before and after measurement of the velocity. When the velocity is high, the presence of various kinds of debris in the stream may lead to external damage to the current meter. In such cases, it is advisable to compare the current-meter readings, before and after measuring the discharge, with the readings from a separate current meter not used in the measurement.

In rivers with intensive channel shifts, the distribution of velocity in a cross-section varies periodically. The choice of velocity verticals must be made by taking into account the velocity distribution at the time of measurement. The use of permanent verticals may lead to systematic errors. If there is intensive shifting of the channel, it is also desirable to use a reduced point method of velocity measurement and a reduced number of verticals (ISO, 1979*b*).

If soundings have been made twice (before and after velocity measurements), the area of water cross-section is computed on the basis of the mean depths from the two soundings. On wide rivers, where the location of sounding verticals usually is determined by distances from an initial point on the shore, the verticals obtained on the two runs may not coincide. In this case, an average cross-section profile of the measurement site is used to select depth values for the discharge computation.

5.3.6.2 Mountain streams

Mountain streams are characterized by high flow velocities, shallow and uneven beds blocked by boulders and debris, transverse and uneven water-surface slopes, and transport of large but varying quantities of stones and pebbles. Measurement or gauging locations with these characteristics should be avoided if possible.

Due to very turbulent flows, it is desirable to use one of the dilution methods of flow measurement on small mountain streams (5.3.4).

Improvements in the channel to make better measurements may be advisable. It may also be desirable to equip the site with a gauging bridge (5.3.2). If it is possible to build a reach with acceptable conditions for current-meter measurements these should be comprised of at least 20 verticals. Measurement of depth by wading rod in mountain streams does not lead to systematic errors. However, the use of a sounding weight with tailfin may lead to underestimates of the depth if the depth is small. For depths of about 1 m, these differences from measurements made by wading rod may amount to about 2.5 to 3 per cent, while for depths of 0.4 to 0.8 m, the difference may be as much as 10 to 15 per cent.

It is best to use the two-point method to measure velocities by current meter. The discharge is calculated as explained in 5.3.2.4.

5.3.6.3 Measurement of unsteady flow

5.3.6.3.1 *Measurement of discharge during floods and on large rivers*

Flood measurements are best made from bridges, cableways or boats. Portable electromechanical winches are available, which can be set up on special trucks, motorcars and tractors. On large rivers, where there are no bridges or cableways, boats, large vessels or ferries are used. Optical or telemetric equipment may be set up on board the vessel and on the bank to determine the position in the channel. Ferries using a cable for the crossing are equipped with electric or mechanical engines for traction by the cable and for lifting and lowering the equipment. Generally, sounding weights of up to 200 kg are necessary because maximum velocities on large rivers may be as great as 3 to 5 m s^{-1}. Soundings of depth also may be made by echo sounder.

For flood measurements on small rivers, remote control or bank-operated traversing systems are particularly suitable. These systems may be portable and can be used at several sites, which need merely to be equipped with a main carrying cable across the river. If such systems are not available, easily transportable duraluminium boats or inflatable rubber rafts with outboard motors and equipment platforms can be used. Locations that are difficult to access may have to be reached by helicopter.

For very high velocities, surface floats or stroboscopic instruments for measuring velocities may be used. The stroboscope has a telescope that is directed towards the surface of the water and a number of rotating mirrors. The speed of rotation of the mirrors is chosen so that a stationary image of the surface of the water is obtained. The velocity of the flow is determined from the speed of rotation of the mirrors. The maximum speed measurable by this method is 15 m s^{-1}, but this maximum is dependent on the height of the observation point above the water surface. Measurements by stroboscope can be made in very turbid flow with floating ice and other solid matter preventing the use of a current meter. The coefficient for converting the surface velocity to the mean velocity at a vertical, determined by similar measurements under less difficult conditions, is usually equal to 0.85–0.90. Measurement of depth is commonly made by echo sounder or a standard cross-section is used.

For wide rivers (3 to 20 km) with several subchannels, measurements by current meter become extremely difficult. In this case, the moving boat method (5.3.7.2) or discharge measurement by acoustic Doppler instruments (5.3.7.5) may be used. Moreover, these are convenient methods when there are short breaks in the ice run or if there is debris. If there is ice or debris in some particular part of the flow, measurements may be made by the float method and by current meter during breaks in occurrence of such debris. Aerial photography using floats may also be employed for wide river measurements.

5.3.6.3.2 *Measurement of discharge in tidal reaches*

Where a measurement section is affected by ocean tides, the following effects must be taken into account:

(a) Continuous change of water level, with and without change of direction of the current;
(b) Continuous change of velocity with time, even at a single point in a vertical with considerable velocity gradients;
(c) Change in the time-distribution of velocity;
(d) Change of direction of the current for the tidal cycle with zero velocity;
(e) Presence of stratified flow with varying density and direction of flows;
(f) Considerable change in the width and cross-section of the flow;
(g) Presence of large-scale turbulence (for example, fluctuations with a period of more than 30 seconds and the amplitude of velocity variations up to 50 per cent) and of seiches.

The discharge of tidal river is generally determined by one of the following methods (ISO, 1974): velocity-area method, volumetric method, or by solving the equation for unsteady flow. The moving boat method (5.3.7.2) or the acoustic Doppler method (5.3.7.5) may also be used, particularly at times when the distribution curve of velocities is close to its usual shape. Other methods, such as the ultrasonic method (5.3.7.3), may also be suitable.

In the method of computation of discharge by the velocity-area method, the velocity is measured during the entire flood-ebb cycle. Measurements are usually made at several points to be able to account for the different directions of flow. At the same time, the water level and the depths at verticals are measured continuously. Then, all measurements are reduced to a single time for which the discharge is calculated.

The accuracy of the velocity-area method is greater if:
(a) The tidal cycle during which the measurement is made is periodic or nearly periodic;
(b) Currents, particularly during the period of maximum flow, are parallel to each other and at right angles to the gauging site at all points;
(c) Curves of horizontal and vertical velocity distributions are of the regular shape encountered at the gauging site;
(d) The transverse profile of the gauging site is uniform and lacks shallow areas.

The site selected should meet as closely as possible the following requirements:
(a) The river bed section should be straight and of regular shape;
(b) The depth of the water at the site should be such that current meters can be used effectively;
(c) The channel section should be stable during the tidal cycle;
(d) The discharge should be concentrated within channels the cross-sections of which can be determined with a fair degree of accuracy;
(e) The site should not be near artificial or natural obstacles causing non-parallel flows;
(f) The gauging site should be clear of vegetation;
(g) Oblique flow, backflow and dead zones should be avoided.

The site should be conspicuously marked on both banks.

To determine discharge during the rise and recession of floods, measurements are made at each vertical during the entire tidal cycle. To determine accurately the moment of zero velocity, measurements begin and end half an hour before and after the tidal cycle. Depending on the equipment available and on the physical characteristics of the selected site, different procedures can be adopted for velocity measurements:
(a) If a sufficient number of boats are available, measurements are made simultaneously at all verticals during the entire tidal cycle;
(b) If only a limited number of boats are available, the chosen verticals are marked by anchored buoys. One or two boats are necessary to carry out the measurements, proceeding successively from one vertical to the next, at intervals of not more than one hour between each vertical. At least one additional boat remains permanently at one reference vertical, carrying out measurements continuously during the entire tidal cycle. In this case, the curves of velocity changes occurring over time at each vertical are plotted by using the concurrent velocities at the reference vertical as a basis of comparison;
(c) If the shape of the tidal curve does not change considerably from day to day and if at least two boats are available, then one of the boats is stationed at the reference vertical to carry out measurements during the whole tidal cycle for each day. The other boat carries out measurements during the whole cycle at each vertical, moving to a new vertical each day. In this case, the number of days required for the whole cycle of observations is equal to the number of velocity verticals;
(d) If there are different tidal amplitudes and if it is not possible to make measurements in many verticals, measurements are carried out at each vertical for the entire cycle at different tidal amplitudes during a lunar month and at spring and neap tides;
(e) If there is considerable pulsation, measurements should be carried out at each vertical with the aid of several current meters set at different heights for periods of 10 to 15 minutes. The mean velocity is determined for the mean period of time;
(f) In the case of oblique currents, use must be made of direct reading current meters or of instruments capable of measuring the angle of deviation.

Where rapid velocity changes occur, the velocity values at the various points in the vertical must be adjusted to a specific time. For this purpose, velocity measurements are either repeated at all points in the vertical by moving from the bottom to the surface, or are measured only at one point at the surface.

For the computation of the discharge at each vertical, a curve of velocity changes with time is plotted, from which the value for a specified time is taken.

For the computation of discharge by the volumetric method, synchronous measurements of the water level are made at the boundaries of the measuring section or sections after their geometrical characteristics (cross-sections, lengths and flooded areas) are determined. An additional gauging station is located on the river above the area of tidal effects so that the discharge attributable to the river can be determined. Where there are transverse slopes in wide estuaries, levels are measured at both banks. The difference in volumes of the tidal prisms during the accounting interval is computed from the change in mean depths and areas of water surface between the boundaries. To determine the mean discharge, the difference in the volume of the total prism is divided by the accounting period minus the inflow into the river.

In the method of computation of discharge from equations of unsteady motion, the solution of the equations of unsteady motion for the section under consideration is simplified by certain assumptions, such as parallel flow and uniform density, and that the channel is prismatic. Measurements are usually made for two typical (high and low) tidal cycles. The measurements are used to calibrate the parameters of the equations.

5.3.6.4 Weed growth in stream channels

Weed growth in rivers can cause relatively large errors. For small rivers, it is advisable, if possible, to construct artificial controls. If this is not possible, discharges should be measured by the velocity area method. For this purpose, a reach of the river 6 to 10 m long should be kept clear of weed growth during the entire season. In addition, the banks should be kept clear of shrubs and high grass over a somewhat larger reach.

The use of toxic substances to impede the growth of vegetation is effective for a short time only. Frequent clearing of the bed may be the most practical method. The weeds growing in the bed may be cut by a special machine attached to a mechanized chainsaw or by the aid of an ordinary scythe.

Flow velocity in each vertical should be measured at three points (at depths of 0.15, 0.5 and 0.85). Where the depth of the vertical is less than 0.40 m, velocity is measured by the single-point method.

In the discharge measurement notes, a short description of the actual state of weed growth should be given.

Because algae and weeds could become entwined in the propeller of the current meter, the instrument should be inspected and cleaned frequently during the measurement process. Where measurements are made at one point only, the regularity with which signals are received must be carefully checked. Experience has been acquired with the use of the electromagnetic method for gauging under such conditions (5.3.7.4).

5.3.7 Non-traditional methods of stream gauging

5.3.7.1 General

Determination of discharge by the velocity-area method, the dilution method and by means of a hydraulic structure (5.4) have certain limitations and are not applicable in some instances. Four relatively new methods of flow measurement in open channels are the moving boat method, the ultrasonic method, the electromagnetic method and the Acoustic Doppler method.

5.3.7.2 Moving-boat method [HOMS E79]

In this method, a boat is fitted with a specially designed component current-meter assembly that indicates an instantaneous value of velocity. A measurement is made by traversing the stream along a preselected path that is normal to the flow. During the traverse, which is made without stopping, an echo sounder records the geometry of the cross-section, and the continuously operating current meter measures the combined stream and boat velocities. These data, collected at some 30 to 40 observation points (verticals) across the path, are converted to discharge. The velocity recorded at each of the observation points in the cross-section is a vector quantity that represents the relative velocity of flow past the meter assembly. This assembly consists of a vane attached to a stainless steel shaft, which, at its upper end, incorporates a dial and pointer for reading the angle between the direction of the vane and the true course of the boat. This is performed by sighting on carefully located markers on the banks. About six runs, in alternate directions, are usually taken and the measurements are averaged to give the discharge (ISO, 1979*a*; Smoot and Novak, 1969).

The discharge is calculated in a similar manner to the conventional velocity-area method by summing the products of the segment areas and average velocities. Because the current meter is located about 1 m below the surface, a coefficient is required to adjust the measured velocity. In large rivers, the coefficient is usually uniform across the section. Investigations on several rivers have shown that the coefficient generally lies between 0.85 and 0.95. The moving boat method provides a single measurement of discharge, and an accuracy of ±5 per cent is claimed at the 95 per cent confidence level.

5.3.7.3 Ultrasonic (acoustic) method [HOMS C73]

The principle of the ultrasonic method is to measure the velocity of flow at a certain depth by simultaneously transmitting sound pulses through the water from transducers located on either side of the river. The transducers, which are designed both to transmit and receive sound pulses, are located on opposite banks, so that the angle between the pulse path and the direction of flow is between 30° and 60°. The difference between the time of travel of the pulses crossing the river in an upstream direction and those travelling downstream is directly related to the average velocity of the water at the depth of the transducers. This velocity can be related to the average velocity of flow of the whole cross-section. The incorporation of an area computation into the electronic processor allows the system to output discharge.

Ideally, the transducers are set at a depth such that they measure the average velocity of flow. In practice, they are ultimately fixed in position so that for any change in stage, they probably will not be at the point of average velocity, and a coefficient is necessary to adjust the measured velocity.

There are two types of ultrasonic systems commonly in use, the first where the transducers are fixed in position and the station is calibrated by current meter, and the second where the transducers are designed to slide on either a vertical or inclined assembly. In the latter method, the system is self-calibrating and therefore no current-meter measurements are necessary. By moving the transducers through a number of paths in the vertical (generally 7 to 10), velocity readings are obtained along these paths. From each set of the readings, vertical velocity curves are established over as large a range in stage as possible. It is then possible first, to estimate a suitable position for the fixing of the transducers in the vertical and, second, to establish a curve of stage against the coefficient of discharge as in the first method.

In rivers with small range in stage, a single-path transducer system may be acceptable. For rivers with large variations in stage, a multipath system with several pairs of transducers may be necessary.

The accuracy of the ultrasonic method depends on the precision with which the travel times can be measured. The several techniques available at the present time are capable of measuring time to very high accuracy (Smoot and Novak, 1969; Herschy and Loosemore, 1974; Smith, 1969; 1971; 1974; Botma and Klein, 1974; Kinosita, 1970; Holmes and others, 1970; Halliday and others, 1975; Lenormand, 1974).

5.3.7.4 Electromagnetic method

The motion of water flowing in a river cuts the vertical component of the Earth's magnetic field, and an electromotive force (emf) is induced in the water that can be measured by two electrodes. This emf, which is directly proportional to the average velocity in the river, is induced along each traverse filament of water as the water cuts the line of the Earth's vertical magnetic field.

Figure I.5.3 shows diagrammatically an electromagnetic gauging station where the coil is placed in the

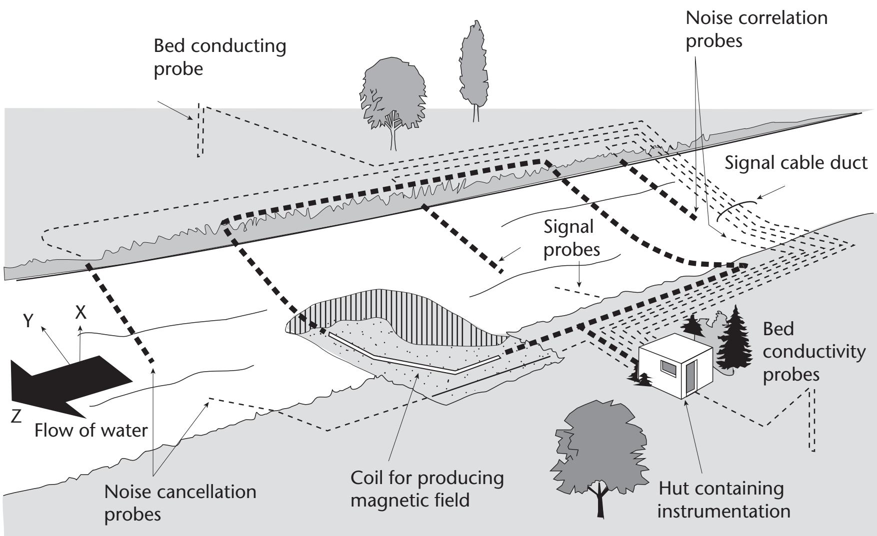

Figure I.5.3. Basic system of the electromagnetic method

bed and the magnetic field is in the x direction, the emf is in the y direction and the streamflow is in the z direction. Faraday's law of electromagnetic induction relates the length of a conductor moving in a magnetic field to the emf generated by the equation (Herschy and Newman, 1974).

In practice, most river beds have significant electrical conductivity that will allow electric currents to flow in the bed. From practical considerations, the induced field will be spatially limited and electric currents flowing in the area outside the field will have the effect of reducing the output potential. Both of the above factors have the effect of reducing the signal and hence the voltage recorded. At an electromagnetic gauging station, it is necessary to measure both the bed and water conductivity.

The most suitable current for the coil is a direct current, the direction of which is reversed a few times per second and an alternating square wave with a frequency of about 1 Hz should be used. A typical installation may have a coil of 12 turns, each of 16 mm^2 double PVC insulated cable, and be supplied with 25 A with a voltage across the coil of about 20 V (Herschy and Newman, 1974).

The electromagnetic method will be suitable for use in rivers with weed growth, high sediment concentration or unstable bed conditions. It gives a continuous record of the average velocity in the cross-section that can be combined with stage to give an on-site output of discharge.

The accuracy depends on the signal processing equipment detecting and measuring small potentials sensed at the voltage probes. It is possible to detect a signal of 100 nV, which represents a velocity of approximately 1 mm s^{-1}. The electromagnetic gauging station requires on-site calibration by current meter or other means and a relation established between discharge and output.

5.3.7.5 Measurement of discharge by acoustic Doppler instruments

5.3.7.5.1 *General*

Developments in acoustic Doppler technology have made these instruments a viable alternative for making measurements of discharge in rivers and large streams. During recent years the instruments and techniques have changed appreciably and it has become possible to use Dopper instruments in small and shallow rivers. All instruments use the Doppler principle to measure velocity from particles (scatters) suspended in the water in order to compute discharge. An acoustic Doppler instrument contains transducers and temperature sensors that are made for operating in water. None of the instruments requires periodic calibrations, unless there is physical damage to the instrument.

5.3.7.5.2 *Doppler principle*

An acoustic Doppler instrument (see Figure I.5.4) measures the velocity of the water using a physical principle called the Doppler shift. This states that if a source of sound is moving relative to the receiver, the frequency of the sound at the receiver is shifted from the transmit frequency. The instrument transmits an acoustic pulse of energy into the water much like a submarine's sonar but at much higher frequencies. This energy is reflected off particles suspended in, and moving with, the water and some of it returns to the instrument. The instrument measures the Doppler shift (change in frequency) of the reflected energy and uses this to compute the velocity of the water relative to the instrument. The reflected pulses have a frequency (Doppler) shift proportional to the velocities of the scatterers they are travelling in along the acoustic beam:

$$V = \left(\frac{F_d}{2\,F_0} \right) C \qquad (5.13)$$

where F_d is the Doppler shifted frequency received at the transducer, F_0 is the transducer transmit frequency, C is the sound speed, and V is the scatterer (water) velocity.

All Doppler instruments operate within a pre-set frequency. The frequency determines under which conditions they are best equipped to measure. An instrument that operates on a lower frequency has

Figure I.5.4. Transducer of an acoustic Doppler instrument installed on a boat

a greater range of distance than an instrument with a higher frequency. The amount and type of particles in the water will also determine the range of the instrument and the quality of the measurements. If there are too few particles in the water, the range will be noticeably shorter and the quality of the data might be compromised.

These principles are true for all of the acoustic Doppler instruments, but different instruments compute discharge in different ways.

5.3.7.5.3 *Acoustic Doppler Current Profilers*

The use of Acoustic Doppler Current Profilers (ADP/ADCP™) has become a common method of measuring river discharge. There are a handful of instruments on the market today designed for use in larger or smaller rivers. They have several traits in common.

ADCP instruments can be mounted on a moving vessel, such as an inflatable boat (see Figure I.5.5). The instrument measures water velocity, depth and vessel path simultaneously to compute discharge. This method computes the discharge as the vessel is crossing the river. The total discharge measurement (ΣQ_1) is completed in a few minutes. The result from one measurement is not enough to give an accurate value of the water flow/discharge; it only gives a freeze-frame picture of the flow. To get an accurate value of the discharge of the river, it is important to take the average of several transects. At least four transects are recommended to calculate the discharge at a site. The actual river discharge estimate will then be the average of the N individual transects discharge values:

$$\sum Q = \frac{\left(\sum Q_1 + \sum Q_2 + \sum Q_3 + \sum Q_4 + \ldots\right)}{N} \tag{5.14}$$

There is need for the instrument to communicate with a computer that computes the discharge. As an ADCP instrument processes the signal reflected off the particles in the water, it divides the water column into a number of discrete segments stacked in the vertical. These segments are called depth cells. An ADCP instrument determines the velocity and direction of each depth cell. At the same time the signal from the bottom, called bottom-track, measures the speed and direction of the boat. This means that the boat does not have to cross perpendicularly to the flow.

The procedures for collecting good data are becoming more standardized worldwide. The number of transects depends on the difference between the discharge measurements. If the discharge for any of four transect differs more than 5 per cent, a minimum of four additional transects should be obtained and the average of all eight transects will be the measured discharge. Sometimes even more transects are made to reduce potential directional

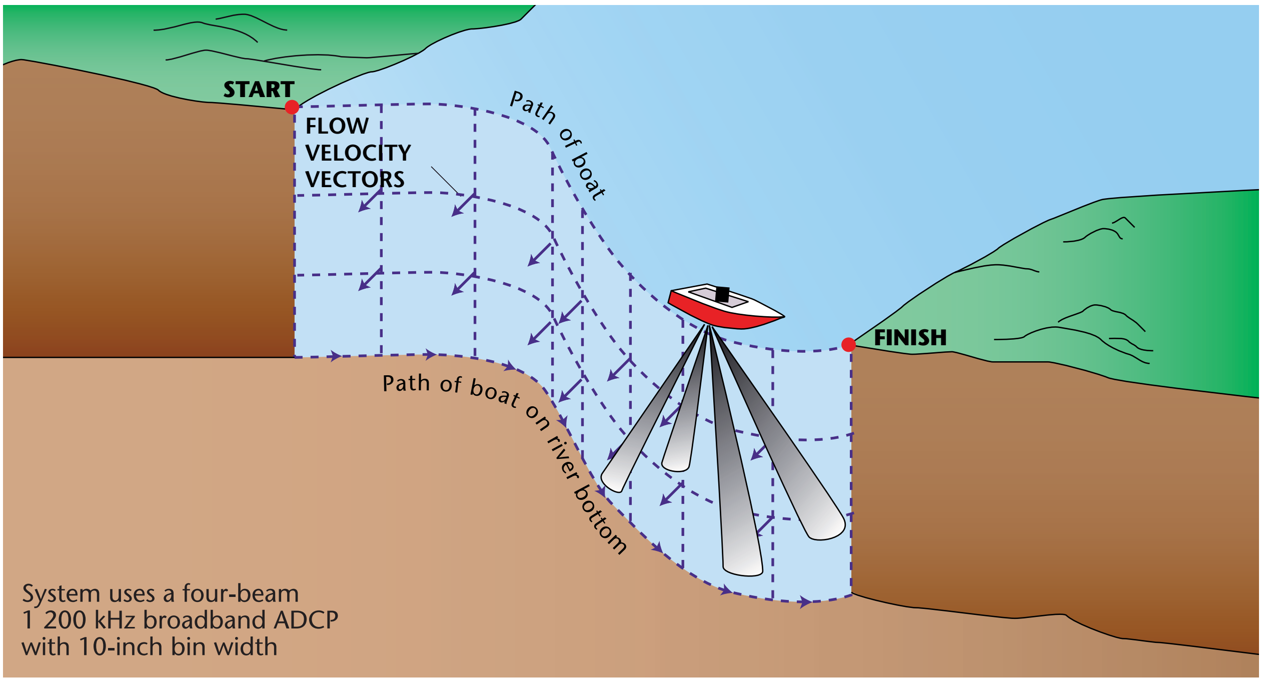

Figure I.5.5. The layout of a typical acoustic Doppler measurement
(Source: United States Geological Survey, http://www.usgs.gov)

biases. The user must configure the instruments before starting the measurements. The choice among different modes of configuration is based on the conditions at the site (water depth, water speed, etc.) at the time of measurement. Use of the correct mode is important for greater accuracy in discharge measurements. The user has to set proper ADCP depth, distance to the banks and make sure that the pitch and roll and the speed of the boat/ instrument is within acceptable limits during the measurements. A bias in any of these can result in a significant bias in the resulting measured discharges.

Another kind of acoustic Doppler profiler instrument makes discharge measurements without using a bottom track. Instead, it measures by use of sections or “verticals”. Depending on the characteristics of the river, the instrument takes 10–20 verticals, each measured for 30–60 seconds, to make a discharge measurement. Such instruments measure the full vertical velocity profile and can easily be suspended from a bridge or suspended with a tag line across the river.

The beams are all oriented in the direction of a two-dimensional (2D) system that makes it possible to measure close to the banks of the river (channel). The user has to set the distance from the bank and the software calculates the cross-sectional area. Since there is no bottom tracking, the instrument must be oriented in the direction of the flow and move across the river in pre-defined segments/verticals. Failure to do this results in inaccurate discharge measurements.

5.3.7.5.4 *Acoustic Doppler Velocimeter*

An Acoustic Doppler Velocimeter (ADV) is a single-point current meter designed specifically for low-power measurements in slow-moving water. These meters require much smaller water sampling volumes than traditional current meters.

One type of ADV is Flowtracker, which is currently the only hand-held ADV on the market. The instrument is an alternative to mechanical current meters for making wading discharge measurements. The Flowtracker consists of a probe head attached to a top-setting wading rod with an interface. The interface allows entering the basic parameters required to make a discharge measurement: station, distance, depth and vertical location of the measurements (0.6, or 0.2 and 0.8 of the depth). By using the velocity-area method, it computes discharge by multiplying the channel area and the mean channel velocity.

True 2D or 3D velocity data are output in Cartesian coordinates (XYZ) relative to probe orientation. Only the X component of velocity (V_x) is used for river discharge measurements. The probe direction has to be perpendicular to the tag line to ensure proper discharge calculations. The operator does not have to estimate the flow angle as is required for 1D current meters.

5.3.7.5.5 *Discharge measurements from fixed platform*

In addition to use for vessel mounted discharge measurements, an acoustic Doppler instrument can be used on fixed platforms to compute the discharge in rivers. The instrument is normally mounted from an underwater structure facing perpendicular to the river flow, and measures water velocity in a two-dimensional plane at multiple points. These instruments are often called Acoustic Doppler Velocity Meters (ADVM) (Gotvald, 2005).

The water velocity meaured by the ADVM is used to compute the mean velocity of the river channel. This is called the index velocity of the river. By using the index velocity, the discharge can be computed in different ways. This is called the index-velocity method. An ADVM gives the opportunity to measure discharge in a river with no or poor stage/discharge relationship. The index-velocity method is basically computing the discharge from the equation $Q = VA$, where Q is the total discharge, V is the mean velocity and A is the channel area. Use of ADVMs on fixed platforms to provide index velocity measurements for river discharge has increased recently.

5.4 STREAM-GAUGING STATIONS

5.4.1 Purpose of stream-gauging stations

The purpose of stream-gauging stations is to provide systematic records of stage and discharge. Continuous streamflow records are necessary in the design of water supply and waste systems, in designing hydraulic structures, in the operations of water management systems, and in estimating the sediment or chemical loads of streams, including pollutants.

Since continuous measurement of discharge is not usually feasible, unless one of the methods in 5.3.7.3 and 5.3.7.4 is used, records of discharge are computed from the relationship between stage and discharge, as defined by periodic discharge measurements and a systematic record of stage, or from a measuring structure that has been calibrated in either a laboratory or the field.

5.4.2 Selection of site

The selection of streams to be gauged should be governed by the principles of network design (2.4) and the proposed use of the data. The selection of a particular site for the gauging station on a given stream should be guided by the following criteria for an ideal gauge site:

(a) The general course of the stream is straight for about 100 m upstream and downstream from the gauge site;
(b) The total flow is confined to one channel at all stages and no flow bypasses the site as subsurface flow;
(c) The stream bed is not subject to scour and fill and is free of weeds;
(d) Banks are permanent, high enough to contain floods, and free of brush;
(e) Unchanging natural controls are present in the form of a bedrock outcrop or other stable riffle during low flow, and a channel constriction for high flow, or a fall or cascade that is unsubmerged at all stages to provide a stable relationship between stage and discharge. If no satisfactory natural low-water control exists, then installation of an artificial control should be considered;
(f) A site is available, just upstream from the control, for housing the stage recorder where the potential for damage by drifting ice or water-borne debris is minimal during flood stages. The elevation of the stage recorder itself should be above any flood likely to occur during the life of the station;
(g) The gauge site is far enough upstream from the confluence with another stream or from tidal effect to avoid any variable influences which the other stream or the tide may have on the stage at the gauge site;
(h) A satisfactory reach for measuring discharge at all stages is available within reasonable proximity of the gauge site. It is not necessary that low and high flows be measured at the same stream cross-section;
(i) The site is readily accessible for ease in the installation and operation of the gauging station;
(j) Facilities for telemetry or satellite relay can be made available, if required;
(k) If ice conditions occur, it would still be possible to record stage and measure discharge;
(l) The flow in the channel section containing the gauging site is subcritical at all stages;
(m) There are no waves and ripples on the water surface in the vicinity of the gauging site.

In many instances, it may be impossible to meet all of these criteria. Judgement is then required to select the most suitable site for the gauge.

5.4.3 Stage-discharge controls

The physical element or combination of elements that control the stage-discharge relationship is known as a control. The major classification of controls differentiates between section control and channel control. Another classification differentiates between natural and artificial controls.

Section control exists when the geometry of a single cross-section is such as to constrict the channel, or when a major downward break in bed slope occurs at a cross-section. The constriction may result from a local rise in the stream bed, as at a natural riffle or rock ledge outcrop or at a constructed weir or dam. It may also result from a local constriction in width, which may occur naturally or may be caused by some man-made channel encroachment, such as a bridge with a waterway opening that is considerably narrower than the width of the natural channel.

Channel control exists when the geometry and roughness of a long reach of channel downstream from the gauging station are the elements that control the relationship between stage and discharge. The length of channel that is effective as a control increases with discharge. Generally, flatter stream gradients will result in longer reaches of channel control.

A low dam, weir or flume is often built in the channel to provide an artificial control. Such controls are usually submerged by high discharges, but they provide a stable stage-discharge relationship in the low to medium flow range.

The two attributes of a good control are resistance to change – ensuring stability of the stage-discharge relationship – and sensitivity, whereby a small change in discharge produces a significant change in stage.

5.4.4 Measuring structures

At some gauging sites it is feasible to utilize an artificial control of such shape that head-discharge relationships can be determined without calibration, that is, by the application of a discharge formula. There is a set of weirs and flumes that have well-established relationships between head and discharge. However, only under favourable field conditions can the established formulae for some types of weirs and flumes be applied accurately. If these structures are used to measure flow directly from water level readings, it is important that care be taken in their construction and operation and that the most suitable formulae be used (WMO, 1986*b*; ISO, 1977*b*, 1980, 1983, 1984, 1989).

Under less favourable conditions, in situ calibration is necessary to establish the extent of the departures from the standard formulae or to develop the head-discharge relationship. It is particularly important at low flow to measure periodically the discharge by other means in order to detect changes in the discharge coefficient caused by sediment deposits in the pool or growth of algae on the weir or flume.

The material in this Guide is limited to the general considerations involved in the selection and use of weirs and flumes at gauging stations. Specific information on their geometries and head-discharge formulae are presented in the *Use of Weirs and Flumes in Stream Gauging* (WMO-No. 280).

5.4.4.1 Scope

Weirs and flumes for use at gauging stations may be catalogued into three groups:
(a) Thin-plate weirs generally used on small, clear-flowing streams or small research watersheds;
(b) Flumes used on small streams and canals conveying sediment and debris or in other situations where the head loss associated with thin-plate weirs is unacceptable;
(c) Broad-crested, triangular-profile and round-shaped weirs used on larger streams.

Weirs and flumes may be free-flowing or submerged. In the first case, the discharge is a function of the headwater elevation, and accurate calibrations are possible. For submerged conditions, the discharge is a function of both the headwater and tailwater elevations, and less accuracy is obtained by use of laboratory calibrations. At many sites, weirs or flumes are used to measure only the lower range of discharge, and the stage-discharge relationship for the upper range of discharges is determined by direct methods.

5.4.4.2 Selection of structure

The choice of a measuring structure depends on costs, the characteristics of the stream and channel at the site, the range of discharges, the accuracy desired and the potential head loss. Criteria to be considered in choosing a structure include:
(a) Cost is usually the major factor in deciding whether or not a measuring structure is to be built. The cost of the structure is affected most by the width of the stream and the type or condition of the bed and bank material. Stream width governs the size of the structure, and bed and bank material govern the type of construction that must be used to minimize leakage under and around the structure;
(b) Channel characteristics and flow conditions influence the design of the measuring structure. Factors controlling velocity or Froude number, sediment loads and the stability of the bed need to be considered in the structure design;
(c) The range of discharge, range of stage, desired sensitivity and allowable head loss must also be considered in structure design and positioning. Submergence by high flows or from backwater influence both the design and elevations of the structure. The sensitivity, that is, the change in stage corresponding to change in discharge at very low flows, may dictate whether a V-crest or flat crest is appropriate;
(d) Cheap, portable weirs made of canvas and light metal plates, for example, may be used on small rivers for limited periods of time.

5.4.4.3 Measurement of head

The head over the structure is usually measured at a distance upstream from the structure equal to about three times the depth of water, h_{max}, on the control at the maximum stage for which the section control is effective. Some special weir shapes and all flumes require that stage be measured at specific distances from the control section that differ from the general rule of 3 x h_{max}. The locations for the gauge or gauge intake for these special cases are described in the *Use of Weirs and Flumes in Stream Gauging* (WMO-No. 280). The zero of the gauge should be set at crest elevation and should be checked regularly.

5.4.4.4 Operation of measuring structures

Both the channel and structure are subject to changes with time that may affect the head-discharge relationship. Sand, rocks or debris may be deposited in the approach section or on the structure itself. Algae may grow directly on the crest of the structure during summer and ice may form on the structure during winter.

For optimum accuracy the approach channel to weirs should be kept clean and free of any accumulation of silt or vegetation. The structure must be kept clean and free of debris, algae and ice. Damage to critical parts of the structure should be repaired.

The datum of the gauge should be checked periodically. Periodic discharge measurements should also be made to define possible changes in the original calibration.

5.4.5 Stage-discharge relationships

5.4.5.1 General

The stage-discharge relationship for most gauging stations is defined by plotting the measured discharges as the abscissa and the corresponding stage as the ordinate (ISO, 1981). The shape of the stage-discharge relationship is a function of the geometry of the downstream elements of the channel that act as the control. When plotted on rectangular coordinate paper, the relationship is generally concave downwards (depends on the exponent value) since discharge often can be described by a power function of the flow depth. Hence, when plotted on logarithmic coordinate paper, the medium- and high-stage sections of the relationship are often approximately linear if the stage represents the effective head on the control for medium and high stages. If this is not linear, the stage-discharge relationship is typically comprised of two or more segments because of shifts in geometry and/or channel resistance. The stage-discharge relationship can readily be expressed by a mathematical equation derived from the available measurements. This equation can be determined by graphical methods or regression methods. Independent of what method is used for deriving the stage-discharge relationship, its accuracy is determined by:

(a) The number of available measurements;
(b) The spread of the measurements;
(c) The average discharge measurement uncertainty.

An estimated stage-discharge relationship should not be extrapolated. Where it is desirable to extrapolate, the application of indirect methods based on the physical conditions of the actual channel and hydraulic control is recommended.

At many sites, the discharge is not a unique function of stage, and additional variables must be measured continuously to obtain a discharge record. For example, in situations where variable backwater at the gauge is caused by a downstream tributary, by tidal effect or by downstream reservoir operation, an auxiliary stage gauge must be installed to measure continuously the fall of the water surface in the gauged reach of the channel. Where flow is unsteady and the channel slopes are flat, the rate of change of stage can be an important variable, and a given discharge that occurs on a rising stage will have a lower gauge height than the same discharge occurring on a falling stage.

5.4.5.2 Stability of stage-discharge relationships

The stability of a stage-discharge relationship is directly related to the stability of the control. For natural section controls, a rock-ledge outcrop will be unaffected by high velocities. Boulder, gravel and sandbar riffles are likely to shift. Boulder riffles are the most resistant to movement, and sandbars are the least. Of the natural channel controls, those found in sand-channel streams are the most likely to change as a result of velocity-induced scour and deposition.

The growth of aquatic vegetation on section controls increases the stage for a given discharge, particularly in the low-flow range. Vegetal growth on the bed and banks of channel controls also affects the stage-discharge relationship by reducing velocity and the effective waterway area. In temperate climates, accumulation of water-logged leaves on section controls during autumn may clog the interstices of alluvial riffles and raise the effective elevation of natural section controls. The first ensuing stream rise of any significance usually clears the control of leaves.

Ice cover also affects the stage-discharge relationship of a stream by causing backwater that varies in effect with the quantity and nature of the ice. If the section control remains open and if the gauge is not too far from the control, there probably will be little or no backwater effect even though the entire pool is ice covered. The only effect of the ice cover will be to slow the velocity of approach, and that effect probably will be minor. However, if the gauge is a considerable distance upstream from the riffle, surface ice on the pool may cause backwater when the covered reach of the pool becomes a partial channel control.

Surface ice forming below a section control may jam and dam water sufficiently to cause backwater effects at the control. Anchor ice may build up the bed or control to the extent that a higher than normal stage results from a given discharge. The magnitudes of ice effects can be determined accurately only by measuring the discharges, observing the corresponding stages and analysing the differences between the observed stage and the discharge corresponding to the open-water stage-discharge relationship.

The various additional conditions that have to be taken into account in making discharge measurements under ice conditions and the procedures for making such measurements are described in 5.3.2.5.

Artificial controls eliminate or alleviate many of the undesirable characteristics of natural section controls. Not only are they physically stable, but also they are less subject to the cyclic or progressive growth of aquatic vegetation. Algal slimes that sometimes form on artificial controls can be removed with a wire brush, and the controls can be self-cleaning with regard to fallen leaves. In moderately cold climates, artificial controls are less likely to be affected by the formation of winter ice than are natural controls. However, even when the artificial control structure is unchanged, the stage-discharge relationship may be affected by changes in the velocity of approach caused by scour and/or fill, or by vegetal growth in the approach channel.

5.4.5.3 Frequency of discharge measurements

Factors to be considered in scheduling the number and distribution of discharge measurements throughout the year include:
(a) Stability of stage-discharge relationship;
(b) Seasonal discharge characteristics and variability;
(c) Accessibility of the gauge in various seasons.

Many discharge measurements are necessary at a new station to define the stage-discharge relationship throughout the entire range of the stage. Periodic measurements are then necessary to define changes in the stage-discharge relationship. A minimum of 10 discharge measurements per year is recommended.

Adequate definition of discharge during flood and under ice conditions is of prime importance. It is essential that the measurement programme provides for non-routine measurement of discharge at these times.

Where it is important to record streamflow continuously throughout the year, discharge measurements should generally be made more frequently when the stream is under ice cover.

During freeze-up and break-up periods, measurements should be obtained as often as possible because of the extreme variability of flow. In midwinter, the frequency of the measurements will depend on climate, accessibility, size of stream, winter runoff characteristics and the required accuracy. In very cold climates, where discharge follows a smooth recession curve, fewer measurements are required than for a stream in a climate of alternate freezing and melting.

5.4.6 Computation of mean gauge height of a discharge measurement [HOMS E71]

Stage and corresponding time should be noted at intervals to identify segments of total discharge with time and stage. Usually the stage at the mid-time of the measurement or the average of the stage at the beginning and end of the measurement can be used as the mean stage corresponding to the measured discharge. If the stage does not change linearly with time the following weighting procedure should be used, where $\overline{h}$ is the weighted stage and Q_1, Q_2,... Q_N are segments of discharge corresponding to stages h_1, h_2,... h_N:

$$\overline{h} = \frac{Q_1 h_1 + Q_2 h_2 + \ldots + Q_N h_N}{Q_1 + Q_2 + \ldots + Q_N} \quad (5.15)$$

5.5 SEDIMENT DISCHARGE AND YIELD

5.5.1 General [HOMS E09]

Sediment is transported by flowing water in different ways. The sediment grains may be moved by saltation, rolling or sliding on or near the bed or may be swept away from it and kept in suspension. The type of movement experienced by the grains depends upon their physical characteristics (size and form of particles, specific weight, etc.) and upon the grain-size composition of the sediment, as well as upon flow velocities and depths. The different phases of sediment transportation generally occur simultaneously in natural streams, and there is no sharp line of demarcation between them. For convenience, sediment discharge is divided into two categories: suspended-sediment and bed-material discharge. The latter consists of grains sliding, rolling or saltating on or near the bed.

This chapter provides guidance on the collection of sediment-discharge data. For each phase of transport, a more in-depth discussion of this topic can be found in the *Manual on Operational Methods for Measurement of Sediment Transport* (WMO-No. 686).

5.5.2 Selection of site

The same criteria used for the selection of a site for a water-discharge measurement should be used in selecting a site for measuring sediment transport (5.3.2.1 and 5.4.2).

5.5.3 Measurement of suspended-sediment discharge

5.5.3.1 Sampling instruments and in situ gauges [HOMS C10]

Several types of suspended-sediment samplers are in use, for example, instantaneous, bottle, pumping or integrating. However, only some of these are designed so that the velocity within the cutting circle of the sampler intake is equal to the ambient stream velocity. This feature is essential so that the samples obtained are truly representative of the suspended-sediment discharge at the point of measurement. The well-designed sampler faces the approaching flow, and its intake protrudes upstream from the zone of disturbance caused by the presence of the sampler.

Instantaneous samples are usually taken by trap samplers consisting of a horizontal cylinder equipped with end valves that can be closed suddenly to trap a sample at any desired time and depth. The very simple bottle sampler is corked or provided with an orifice of variable diameter, or wide open. As soon as the bottle is opened and air within the bottle is being displaced by the sample, bubbling takes place at the mouth, which slows the filling process. Consequently, bottle-sampling is not actually instantaneous.

The pumping sampler sucks the water-sediment mixture through a pipe or hose, the intake of which is placed at the sampling point. By regulating the intake velocity, the operator can obtain a sample that is representative of the sediment concentration at the point of measurement. The integrating sampler consists of a metallic streamlined body equipped with tail fins to orient it into the flow. The sample container is located in the body of the sampler. An intake nozzle of variable diameter projects into the current from the sampler head. An exhaust tube, pointing downstream, permits the escape of air from the container. Valve mechanisms enclosed in the head are electrically operated by the observer to start and stop the sampling process.

A relatively new method of in situ determination of suspended-sediment concentration is the use of optical or nuclear gauges. The working principle of these instruments is that a visible light of X-ray emitted by a source with constant intensity is scattered and/or absorbed by the suspended-sediment particles. The decrease of intensity measured by a photoelectric or nuclear detector situated at constant distance from the source is proportional to the sediment concentration, if other relevant characteristics of water and sediment (chemical, mineral composition, etc.) remain unchanged.

The overall design of suspended-sediment samplers should be checked by towing them in still water at a known velocity or by holding them in flowing water of known velocity. The optical and nuclear gauges must be calibrated by simultaneous and repeated sampling in sediment-laden flumes and natural streams.

5.5.3.2 Measurement procedure

Samples of suspended sediment in streams are taken in the discharge-measuring cross-sections, but not necessarily in the velocity-measuring verticals. In lakes, the locations of sampling verticals are scattered over an area, because here the measurements are usually aimed at the determination of distribution of sediment concentration in time and space. The samplers are suspended in the water on a rod or on a wire.

In streams, there are two methods that give comparative results:

(a) Equal discharge increment (EDI) method: The cross-section is divided into 3 to 10 subsections of about equal discharge. A depth-integrated sample is taken at each vertical in the centroid of each subsection by lowering the sampler from the stream surface to the bed and back at a uniform transit rate. This gives a discharge-weighted sample for each centroid;

(b) Equal transit rate (ETR) method: The stream width is divided into 6 to 10 equal distances separated by the verticals and one depth-integrated sample is taken at each vertical at a constant transit rate. In the latter case, all samples can be composited into a single representative discharge-weighted sample (ISO, 1977*b*).

By using a point sampler, samples may also be taken at evenly spaced points at each vertical mentioned above, and the sediment concentrations obtained are weighted by the ratio of the velocity at the given point to the mean velocity in the vertical. In practice this procedure can be combined with the mid-section method of discharge measurement

(5.3.2.4) because the velocity measuring and sampling verticals coincide.

The optical and nuclear sediment gauges may be used both for point- and depth-integrating measurements, provided the electrical signals from the detector are summarized by a scalar. Depending upon the statistical characteristics of counting by a particular instrument, the usual counting period is three to five minutes.

5.5.3.3 Determination of sediment concentration

Suspended-sediment samples are usually processed and analysed in special laboratories for the determination of the sediment concentration. Evaporation, filtration or displacement methods are generally used for this purpose. In general, the evaporation method is suitable for use with low concentrations. Filtering may be used for samples with medium to high concentrations. The displacement method, however, is suitable only when the concentration is high (WMO, 1989). The sample is usually allowed a settling time of one to two days, the water is then carefully drained off and the remaining sediment is oven dried at a temperature of about 110°C, and weighted. If the sediment is separated by evaporation, a correction must be made for dissolved solids. The concentration of suspended sediment is the weight of dried sediment contained in a unit volume of the sediment-water mixture and is expressed in mgl^{-1}, gl^{-1} m^{-3} or in kg m^{-3}.

Sediment samplers have been standardized in some countries to have a container capacity of one litre or less. In such cases, sampling should be repeated until the required volume of sediment sample is obtained (ISO, 1977*b*).

The intensities of light or X-ray indicated by the submerged photoelectric or nuclear probes of in situ gauges should be divided by the intensity measured in clear water and the sediment concentration corresponding to this ratio is read from the calibration curves of these instruments.

5.5.3.4 Computation of suspended-sediment discharge

For the EDI method, the weighted mean sediment concentration, $\overline{c}_s$, in kg m^{-3} for the entire cross-section is computed as:

$$\overline{c_s} = \frac{\sum c_q\, q_p}{\sum q_p} \tag{5.16}$$

where q_p is the partial discharge in the subsection in m^3 s^{-1}, and c_q is the discharge weighted concentration in the vertical at the centroid of the subsection in kg m^{-3} (ISO, 1977*b*).

For the ETR method the concentration of the composite sample is the weighted mean concentration in the entire cross-section. The suspended sediment discharge, Q_s, is computed as:

$$Q_s = \overline{c}_s\, Q \tag{5.17}$$

where Q_s is in kg s^{-1} and Q is the stream discharge in m^3 s^{-1}.

5.5.3.5 Continuous record of suspended-sediment discharge

A continuous record of suspended-sediment discharge may be computed from a record of stream discharges and systematic samples of suspended-sediment concentration. The samples should be taken daily during periods of low and mean flow and more frequently during floods. The most valuable information concerning the time-variation of concentration and its peak values can be obtained by the continuous recording of signals supplied by the photoelectric or nuclear suspended-sediment gauges during flood periods. The peak in concentration usually precedes peak flow, and loops can be observed on plots of the water discharge versus sediment discharge, similar to those in stage-discharge rating curves during floods.

The samples or observation records are collected at a single vertical in the cross-section, preferably using the depth-integrating procedure. The relation between the concentration at this vertical and the mean concentration in the section must be established by detailed measurements of the distribution of sediment in the cross-section, as outlined in 5.5.3.2. This relation is not necessarily linear and constant throughout the year, nor in all ranges of sediment concentration.

5.5.3.6 Use of remote-sensing techniques

The determination of the amount of sediment in water is based on the reflectance of radiation in the visible and IR parts of EMS (WMO, 1972). In general, reflection is a non-linear function of the concentration of suspended sediments with maximum reflectance dependent on wavelength and suspended sediment concentration. Because turbidity and suspended sediments are closely linked in most water bodies, estimates of turbidity can also be made. A limitation on the use of this technique is the need to collect field data to calibrate the relationship between suspended sediments and reflectance. Furthermore, scanner data can be used without calibration data to map relative suspended sediment concentrations in river plumes and draw conclusions about sediment deposition patterns in lakes and estuaries. A good review of applications of remote-sensing to estimation of suspended sediments can be found in Dekker and others (1995).

5.5.4 Measurement of bed-material discharge

5.5.4.1 Instrumentation [HOMS C12]

The field measurement of bed-material discharge is difficult because of the stochastic nature of the sediment movement and because the phenomenon takes place in the form of ripples, dunes and bars. No single apparatus has proved to be completely adequate for trapping the largest and smallest sediment particles with the same efficiency, while remaining in a stable, flow-oriented position on the stream bed, and still not altering the natural flow pattern and sediment movement. Available samplers can be classified into three types: basket, pan and pressure-difference (ISO, 1977*c*). Another type of sampler is the slot or pit-type sampler which is adaptable for use mainly in relatively small rivers and particularly for experimental study or calibration of samplers (Emmett, 1981).

Basket samplers are generally made of mesh material with an opening on the upstream end, through which the water-sediment mixture passes. The mesh should pass the suspended material but retain the sediment moving along the bed.

Pan samplers are usually wedge-shaped in longitudinal section and are located so that the point of the wedge cuts the current. The pan contains baffles and slots to catch the moving material.

Pressure-difference samplers are designed to produce a pressure drop at the exit of the sampler which is sufficient to overcome energy losses and to ensure an entrance velocity equal to that of the undisturbed stream. A perforated diaphragm within the sampler forces the flow to drop its sediment into the retaining chamber and to leave through the upper exit.

It is necessary, because of several uncertainties involved in sampling, to determine an efficiency coefficient for each type of sampler. The calibration generally takes place in a laboratory flume, where the bed-material discharge can be directly measured in a sump at the end of the flume, although uniform-transport conditions over the width and length of the flume are difficult to maintain. Even under favourable conditions, efficiency factors are not easily determined because they vary according to, among others, the grain-size composition of the bed material and the degree of fullness of the sampler. An efficiency of 60 to 70 per cent can be regarded as satisfactory.

5.5.4.2 Measurement procedure

Bed-material discharge is determined from the amount of sediment trapped per unit time in a sampler located at one or more points on the stream bed. There should generally be 3 to 10 measurement points in a cross-section, depending on the width of the cross-section and the sediment concentration distribution. In determining the distribution of sampling points, it should be noted that, except during flood periods, bed-material transport takes place only in a part of the stream width.

The inclusion of a zero measurement in the computation of bed-material discharge can lead to uncertainties in the result even though the sampling point may be situated between two moving strips of the stream bed. Uncertainties can also occur if a measured rate of transport is extended over a segment of the cross-section with low or zero sediment movement.

On gravel-bed streams, of which partial bed-material movement is most characteristic, different types of acoustic detectors can help to solve this problem. Submerged to a depth near the bed, these detectors pick up the sound of moving gravel, indicating the movement of bed material at this particular point. Moreover, the intensity of the sound and that of the sediment transport may be correlated.

The samplers (see, for example, Figure I.5.6) are lowered to the bottom and held in position by a rod or a wire. The duration of the sampling period is usually a few minutes, depending on the dimensions of the sampler and on the intensity of the sediment transport. When low-flow velocities exist near the bed, the downstream forces are reduced and the sampler tends to dive into the stream bed and scoop up bed material that is not in transport. A similar tendency can develop during an abrupt or incautious lifting of the sampler.

Measurements should be made at various stream discharges so that a rating may be prepared showing the relationship between stream discharge and bed-material discharge. Owing to the highly complex mechanism and random nature of sediment transport and to the errors of sampling, one single catch at a measuring point can provide a very uncertain estimate of the true bed-material transport. Therefore, repeated sampling should be carried out at each point. The number of repetitions depends on the local circumstances. However, statistical analyses of field data resulting from up to 100 repetitions have shown that only the bed-material discharge can be measured with restricted accuracy, unless an impracticably large number of samples are taken at each point.

5.5.4.3 Computation of bed-material discharge

The sediment collected in the sampler is dried and weighed. The dry weight, when divided by the time taken for the measurement and the width of the sampler, gives the bed-material discharge per unit width of stream at the point of measurement, q_b. A curve showing the distribution of q_b in the stream width can be constructed based on data obtained at the sampled points. The area enclosed between this curve and the water-surface line represents the total daily bed-material discharge over the entire cross-section Q_b. The value of Q_b can also be computed by using the measured q_b data as:

$$Q_b = \frac{q_{b1}}{2} x_1 + \frac{q_{b1} + q_{b2}}{2} x_2 + \text{K} \ldots + \frac{q_{bn-1} + q_{bn}}{2} x_{n-1} + \frac{q_{bn}}{2} x_n \qquad (5.18)$$

where Q_b is in kg s^{-1}, q_b is in kg s^{-1} m^{-1} and x is in metres. The variable x represents the distance between sampling points, between a marginal point and the edge of the water surface, or that of the moving strip of stream bed.

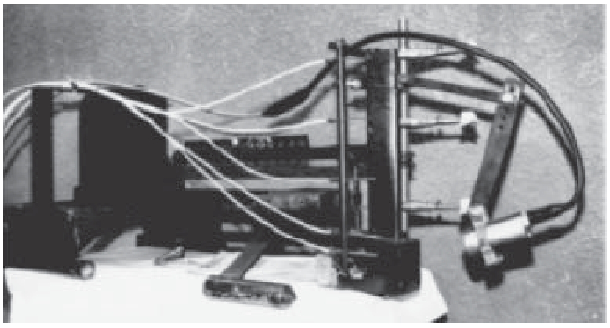

Figure I.5.6. Delft Nile sampler consisting of a bed-load and suspended-load sampler as well as an underwater video camera

The existence of dams trapping most of the sediment transported by upstream river reaches offers the possibility of estimating the annual or seasonal sediment discharge by successively surveying suitable selected profiles of the reservoir and by computing the volumes occupied by the trapped sediment. This method, combined with regular suspended-sediment sampling upstream and downstream of the dam, can provide acceptable estimates of bed-material discharge.

5.5.4.4 Continuous record of bed-material discharge

A continuous record of bed-material discharge can be obtained by relating bed-material discharge to stream discharge or other hydraulic variables with available records. This relationship can be assumed approximately linear for water discharges above the limiting value corresponding to the beginning of sediment movement because the tractive force of the flow increases in direct proportion to the increase in stream discharge. Bed-material transport is of primary interest in all investigations concerning stream bed-changes.

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CHAPTER 6

GROUNDWATER

6.1 GENERAL [HOMS L]

Groundwater underlies most of the Earth's land surface. In many areas it is an important source of water supply and supports the flow of rivers. In order to understand the full extent of the hydrological system, it is necessary to understand the groundwater system (Fetter, 1994; Freeze and Cherry, 1979). The purpose of this chapter is to provide an overview of those basic concepts and practices that are necessary to perform an appraisal of groundwater resources. Generally, a groundwater resource appraisal has several key components:

(a) Determination of the types and distribution of aquifers in the area of investigation;
(b) Evaluation of the spatial and temporal variations of groundwater levels (potentiometric surface) for each aquifer, resulting from natural and man-made processes. The construction of wells and measurement of water levels facilitates this aspect;
(c) Assessment of the magnitude and distribution of hydraulic properties, such as porosity and permeability, for each aquifer. This is a requirement for any type of quantitative assessment;
(d) An understanding of the processes facilitating or affecting recharge to and discharge from each aquifer. This includes the effective amount of precipitation reaching the water table, the effects of evapotranspiration on the water table, the nature of groundwater–surface water interaction, and the location of and amount of discharge from springs and pumped wells;
(e) An integration of the groundwater data in order to corroborate information from multiple sources, understand the relative importance of the various processes to the groundwater system, and appraise the capacity or capability of the groundwater system to meet general or specific (usually water supply) goals. This can be facilitated with the development of predictive tools using various analytical options that range from water budgets to computer-based digital groundwater flow modelling.

6.2 OCCURRENCE OF GROUNDWATER

6.2.1 Water-bearing geological units

Water-bearing geological material consists of either unconsolidated deposits or consolidated rock. Within this material, water exists in the openings or void space. The proportion of void space to a total volume of solid material is known as the porosity. The interconnection of the void space determines how water will flow. When the void space is totally filled with water the material is said to be saturated. Conversely, void space not entirely filled with water is said to be unsaturated.

6.2.1.1 Unconsolidated deposits

Most unconsolidated deposits consist of material derived from the breakdown of consolidated rocks. This material ranges in size from fractions of a millimetre (clay size) to several metres (boulders). Unconsolidated deposits important to groundwater hydrology include, in order of increasing grain size, clay, silt sand and gravel.

6.2.1.2 Consolidated rock

Consolidated rocks consist of mineral grains that have been welded by heat and pressure or by chemical reactions into a solid mass. Such rocks are referred to as bedrock. They include sedimentary rocks that were originally unconsolidated, igneous rocks formed from a molten state and metamorphic rocks that have been modified by water, heat or pressure. Groundwater in consolidated rocks can exist and flow in voids between mineral or sediment grains. Additionally, significant voids and conduits for groundwater in consolidated rocks are fractures or microscopic- to megascopic-scale voids resulting from dissolution. Voids that were formed at the same time as the rock, such as intergranular voids, are referred to as primary openings (Figure I.6.1). Voids formed after the rock was formed, such as fractures or solution channels, are referred to as secondary openings (Figure I.6.1). Consolidated sedimentary rocks important in groundwater hydrology include limestone, dolomite, shale, siltstone and conglomerate. Igneous rocks include granite and basalt, while metamorphic rocks include phyllites, schists and gneisses.

6.2.1.3 Aquifers and confining beds

An aquifer is a saturated rock formation or deposit that will yield water in a sufficient quantity to be considered as a source of supply. A confining bed is a rock unit or deposit that restricts the movement of water, thus does not yield water in usable quantities to wells or springs. A confining bed can sometimes be considered as an aquitard or an aquiclude. An aquitard is defined as a saturated bed which yields inappreciable quantities of water compared to the aquifer but through which appreciable leakage of water is possible. An aquiclude is a saturated bed which yields inappreciable quantities of water and through which there is inappreciable movement of water (Walton, 1970).

6.2.1.4 Confined and unconfined aquifers

In an unconfined aquifer, groundwater only partially fills the aquifer and the upper surface of the water is free to rise and fall. The water table aquifer or surficial aquifer is considered to be the stratigraphically uppermost unconfined aquifer. Confined aquifers are completely filled with water and are overlain and underlain by confining beds. The impedance of flow through a confining bed can allow the water level to rise in a well above the top of the aquifer and possibly above the ground. This situation can result in wells that flow naturally. Confined aquifers are also known as artesian aquifers.

6.2.2 Development of a hydrogeologic framework [HOMS C67]

Information about aquifers and wells needs to be organized and integrated to determine the lateral and vertical extent of aquifers and confining beds. On that basis, determination of such characteristics as the direction of groundwater flow, and effects of hydrological boundaries, can be undertaken. The compilation of the lateral and vertical extent of aquifers and confining beds is commonly referred to as the hydrogeologic framework. To be useful, this concept of a framework needs to be based, as much as possible, on actual and quantitative data about the existence, orientation and extent of each aquifer and confining unit where applicable. Where

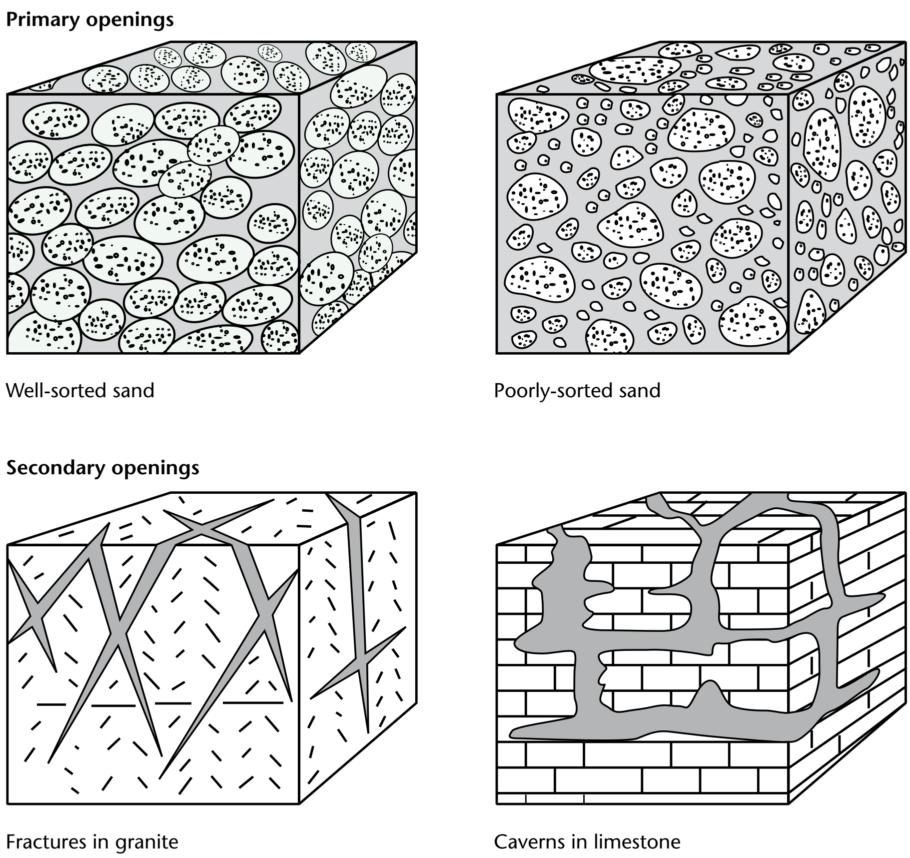


Figure I.6.1. Examples of water-bearing sediments of rocks with primary (intergranular is shown) and secondary (fractured and dissolution are shown) pore space (Heath, 1983) actual data are not available, one must rely on the conceptual knowledge of the subsurface conditions.

The development of a hydrogeological framework requires an accurate view, in a real sense, of the subsurface conditions. This can be accomplished in several direct and indirect ways. Direct methods include recovery of aquifer and confining bed material during the process of drilling, in the form of cuttings and core samples. Indirect methods include sensing earth properties using borehole or surface geophysical properties. A robust approach to collect these data involves combining all available methods, ultimately piecing together information to produce a detailed picture of the aquifer and confining unit extents, thicknesses, orientations and properties.

6.2.2.1 Well-drillers' and geologists' logs

Information about the nature of subsurface materials can be found in the records of construction of wells, mine shafts, tunnels and trenches, and from descriptions of geological outcrops and caves. Of particular usefulness to groundwater studies is the record of conditions encountered during the drilling of a well. This can be done either by the driller or a geologist on site monitoring conditions, by bringing the drill cuttings to the surface and examining any core samples taken. A driller's log or geologist's log (depending on who prepared the information) is a continuous narrative or recording of the type of material encountered during the drilling of a well. Additionally, these logs may contain remarks such as the relative ease or difficulty of drilling, relative pace of advancement and amount of water encountered.

6.2.2.2 Borehole geophysical methods

Borehole geophysical logging is a common approach to discerning subsurface conditions. A sonde is lowered by cable into a well or uncased borehole. As it is lowered or raised, a sensor on the sonde makes a measurement of a particular property or suite of properties. These data are then transmitted up the cable as an analog or digital signal that is then processed and recorded by equipment at the land surface. The data are typically shown in strip chart form, referred to as a log. These measurements provide more objectivity than that of a geologist's log of core or drill cutting samples, allowing for more consistency between multiple sources of data. Table I.6.1 provides a brief overview of the borehole geophysical methods commonly used in groundwater investigations: caliper, resistivity including spontaneous potential (SP), radiation logs including natural gamma, borehole temperature and borehole flow (Keys and MacCary, 1971).

6.2.2.3 Surface geophysical methods

Surface geophysical methods are used to collect data on subsurface conditions from the land surface along transects. Depending on the instrument, various types of probes are either placed in contact or close proximity with the ground surface to produce the measurements. There are four basic surface geophysical methods: seismic, electrical resistivity, gravimetric and magnetic (Zohdy and others, 1974). These are summarized in Table I.6.2. Accurate interpretation is greatly aided by core samples or bore hole geophysical data.

6.2.2.4 Hydrostratigraphic correlation

The integration of hydrogeological information collected from a network of individual wells, surface geophysical transects and geologic outcrops to formulate a large-scale, comprehensive understanding of the lateral extent and vertical nature of aquifers and confining beds in an area, referred to as the hydrogeological framework, relies on the process of correlating those data from different locations. Correlation, in this sense, can be defined as the demonstration of equivalency of units observed at different locations. The essence of the problem for the practitioner is to determine whether an aquifer identified at one location is connected or equivalent to one at other locations. When approaching this type of task, geologists focus on equivalent geologic age units or rock types. The hydrogeologist, however, must be concerned with equivalence from a hydraulic standpoint that may transcend rock type or geologic age. The reliability and accuracy of the resultant hydrogeological framework is directly related to the density of well and transect information. In areas of complex geology and topography, a relatively higher data density is required than in simpler areas.

The approach is to identify a preferably unique lithologic or hydraulic feature that is directly related to an aquifer or confining bed at one location. The feature could be, for example, the presence of a certain layer with a particular composition or colour within or oriented near the aquifer or confining bed under study. This is referred to as a marker unit. A unique signature of particular strata on a borehole geophysical log may be of use. Once identified in the data related to a particular well or location, data from nearby wells are examined for the existence of the same marker. Because of variations in geology and topography, the depth at which the

Table I.6.1. Summary of borehole geophysical methods commonly used in groundwater investigations

Type of log	*Measured property*	*Utility*	*Limitations*
Caliper	Diameter of borehole or well; relationship between the diameter of the hole and the depth	When used in an uncased borehole that shows the nature of the subsurface materials, the borehole is usually washed out to a larger diameter when poorly consolidated and non-cohesive materials are penetrated by the hole. In consolidated rock may reveal the location of fractured zones. May indicate the actual fracture, if large enough, or may indirectly indicate the presence of a fractured zone by an increase in the hole diameter resulting from the washout of friable material.	Caliper sonde has a maximum recordable diameter.
Temperature	Temperature; relationship of temperature to depth	Used to investigate source of water and inter-aquifer migration of water. Frequently recorded in conjunction with other logs, such as electrical logs, to facilitate determination of temperature compensation factors.	
Electrical	Single electrode electrical resistivity or conductivity measurements	Single electrode measurements yield spontaneous potential (SP) and resistance measurements. SP measurements are a record of the natural direct-current potentials that exist between subsurface materials and a static electrode at the surface that vary according to the nature of the beds traversed. The potential of an aquifer containing salty or brackish water is usually negative with respect to associated clay and shale, while that of a freshwater aquifer may be either positive or negative but of lesster amplitude than the salty water. Resistance measurements are a record of the variations in resistance between a uniform 60-Hz alternating current impressed on the sonde and a static electrode at the surface. Resistance varies from one material to another, so it can be used to determine formation boundaries, some characteristics of the individual beds, and sometimes a qualitative evaluation of the pore water. The single electrode log requires much less complex equipment than other types of methods. The data can usually be readily interpreted to show aquifer boundaries near to the correct levels, and the thickness of the formation if greater than about one third of a metre (1 foot). The true resistivity cannot be obtained, only the relative magnitude of the resistivity of each formation. With sufficient records from a uniform area, these relative magnitudes can sometimes be interpreted qualitatively regarding the quality of the water in the various aquifers.	Electrical logs cannot be run in cased holes. Satisfactory logs may not be obtained in the vicinity of power stations, switchyards and similar installations. The sonde must be in contact with the sidewall of the borehole. This may be difficult in boreholes of large diameter.
	Multiple electrode electrical resistivity or conductivity measurements	The multiple electrode log consists of SP, and two or more resistivity measurements. SP is identical to that of the single electrode log. The resistivity measurements show the variations of potential with depth of an imposed 60-Hz alternating current between electrodes spaced at varying distances apart on the sonde. Commonly used electrode spacings are: "short-normal", 0.4064 to 0.4572 m (16 to 18 in); "long-normal", 1.6256 m (64 in) and "long lateral", 5.6896 m (18 ft, 8 in). The radius of investigation about the hole varies with the spacing. The logging instrument consists of a sonde with three or more electrodes spaced at various distances, supported by a multiple conductor cable leading to the recorder, an alternating-current generator and an electrode attached to the recorder and grounded at the surface to complete SP resistivity circuit and cables, reels, winches and similar necessary equipment.	

Type of log	*Measured property*	*Utility*	*Limitations*
Radiation	Radiation from natural materials, usually gamma radiation	Nearly all rocks contain some radioactive material. Clay and shale are usually several times more radioactive than sandstone, limestone and dolomite. The gamma ray log is a curve relating depth to intensity of natural radiation and is especially valuable in detecting clays and other materials of high radiation. The radiation can be measured through the well casing, so these logs may be used to identify formation boundaries in a cased well. Also, they may be used in a dry hole whether cased or uncased.	
	Radiation transmitted through, from, or induced in the formation by, a source contained in the sonde, such as a neutron radiation	Neutron logging equipment contains a neutron radiation source in addition to a counter and can be used in determining the presence of water and saturated porosity.	Exreme care must be taken in the transportation, use and storage of the sonde containing the radioactive source. Governmental licensing may be required.
Borehore flow	Flow velocity; instantaneous or cumulative fluid velocity with depth	A mechanical or electronic flow meter senses variations in fluid velocity in the borehole. When water is pumped from the borehole during logging, variation in contribution of flow with depth can be determined. Can indicate primary sources (fracture zones, sand beds, etc.) of water to borehole. Flow meters based upon heat-pulse methods are best for low velocities.	Can only be used in fluid-filled boreholes or wells

marker is found may be different. If the marker is then identified, it may be postulated that the aquifer or confining bed at a similar relative location as identified in the original well is correlated, and thus may indicate that the aquifer or confining unit is continuous between the data points. If a particular marker is not identifiable at other nearby locations, the available data must be re-examined and additional attempts at correlation made. The inability to make a correlation and define continuity may indicate the presence of a fault, fold or some type of stratigraphic termination of the unit. Knowledge of the geology of the area and how it is likely to affect the continuity and areal variation in the character of aquifer and confining beds is essential. It may be necessary to consult with geologists familiar with the area in order to proceed with this task. It cannot be overstressed that geological complications and the possible non-uniqueness of a marker unit could lead to erroneous conclusions.

6.3 OBSERVATION WELLS

6.3.1 Installation of observation wells

Since ancient times, wells have been dug into water-bearing formations. Existing wells may be used to observe the static water table, provided that the well depth extends well below the expected range of the seasonal water level fluctuations and that the geological sequence is known. An examination should be made of existing wells to ascertain which, if any, would be suitable as observation wells. Existing pumped wells can also be incorporated into the network if the annular space between the outer casing of the well and the pump column allow free passage of a measuring tape or cable for measuring the water level. Whenever existing drilled or dug wells are used as observation wells, the water level in those wells should be measured after the pump has been turned off for a sufficient time to allow recovery of the water level in the well. Abstractions in the vicinity of an observation well should also be stopped for a time long enough for the depth of the cone of depression at the observation well to recover. If new wells are required, the cost makes it necessary to plan the network carefully.

In those parts of aquifers with only a few pumped or recharge wells that have non-overlapping cones of influence, it is generally preferable to drill special observation wells far enough from the functioning wells in order to avoid their influences. The principal advantage of dug wells is that they can be constructed with hand tools by local skilled

Table I.6.2. Summary of surface geophysical methods commonly used in groundwater investigations

Methods	*Property*	*Approach*	*Utility and limitations*
Seismic	The velocity of sound waves is measured. The propagation and velocity of seismic waves are dependent on the density and elasticity of the subsurface materials and increase with the degree of consolidation or cementation.	Sound waves are artificially generated using mechanical means such as blows from a hammer or small explosive charges. Seismic waves radiate from the point source, some travel through the surface layers, some are reflected from the surfaces of underlying materials having different physical properties, and others are refracted as they pass through the various layers. Different approaches are used for reflection and refractions data.	Can provide detailed definition of lithologic contacts if lithologies have contrasting seismic properties. Commonly used in groundwater studies to determine depth to bedrock below soil and unconsolidated sediment horizons. Computer processing of data collected using a gridded approach can provide very detailed 3-dimensional views.
Electrical resistivity	Earth materials can be differentiated by electrical resistivity. Electrical resistivity is also closely related to moisture content and its chemical characteristics, i.e., salinity. Dry gravel and sand have a higher resistivity than saturated gravel and sand; clay and shale have very low resistivity.	Direct or low frequency alternating current is sent through the ground between two metal electrodes. The current and resulting potential at other electrodes are measured. For depth soundings, the electrodes are moved farther and farther apart. As a result of these increasing distances, the current penetrates progressively deeper. The resistivity of a constantly increasing volume of earth is measured and a resistivity versus electrode spacing plot is obtained.	Applicable to large or small areas and extensively used in groundwater investigations because of response to moisture conditions. Equipment is readily portable and the method is commonly more acceptable than the blasting required for seismic methods. The resistivity method is not usable in the vicinity of power lines and metal structures.
Gravimetric	Gravity variations result from the contrast in density between subsurface materials of various types.	The force of gravity is measured at stations along a transect or grid pattern.	The equipment is light and portable, and the field progress is relatively rapid. Altitude corrections are required. The gravimetric survey is a valuable tool in investigating gross features such as depth to bedrock and old erosional features on bedrock, and other features such as buried intrusive bodies. This method is applicable to small or large areas. The results of this method are less detailed than those from seismic or resistivity methods
Magnetic	The magnetic properties of rocks affect the Earth's magnetic field; for example, many basalts are more magnetic than sediments or acid igneous rocks.	The strength and vertical component of the Earth's magnetic field is measured and plotted. Analysis of the results may indicate qualitatively the depth to bedrock and presence of buried dykes, sills and similar phenomena.	Magnetic methods are rapid and low cost for determining a limited amount of subsurface information. The results of this method are less detailed than those from seismic or resistivity methods. It is best suited for broadly outlining a groundwater basin.

labourers. Depths of 3 to 15 m are common, but such wells exist as deep as 50 m or more. Dug wells may be constructed with stone, brick or concrete blocks. To provide passage of the water from the aquifer into the well, some of the joints are left open and inside corners of the blocks or bricks are broken off.

When the excavation reaches the water table, it is necessary to use a pump to prevent water in the well from interfering with further digging. If the quantity of water entering the well is greater than the pump capacity, it is possible to deepen the well by drilling. The technique of excavating wells to the water table and then deepening the well by drilling is common practice in many parts of the world. The finished well should be protected from rain, flood or seepage of surface waters, which might pollute the water in the well and hence the aquifer. The masonry should extend at least 0.5 m above ground level. The top of the well should be provided with a watertight cover and a locked door for safety purposes. A reference mark for measuring depth to water (levelled to a common datum) should be clearly marked near the top of the well.

Where groundwater can be reached at depths of 5 to 15 m, hand boring may be practical for constructing observation wells. In clays and some sandy looms, hand augers can be used to bore a hole 50 to 200 mm in diameter that will not collapse if left unsupported. To overcome the difficulty of boring below the water table in loose sand, a casing pipe is lowered to the bottom of the hole, and boring is continued with a smaller diameter auger inside the casing. The material may also be removed by a bailer to make the hole deeper.

In areas where the geological formations are known in advance and which consist of unconsolidated sand, silt or clay, small-diameter observation wells up to 10 m in depth can be constructed by the drive-point method. These wells are constructed by driving into the ground a drive point fitted to the lower end of sections of steel a pipe. One section is a strainer (filter) consisting of a perforated pipe wrapped with wire mesh protected with a perforated brass sheet. Driven wells, 35 to 50 mm in diameter, are suitable for observation purposes.

To penetrate deep aquifers, drilled wells are constructed by the rotary or percussion-tool methods. Because drilling small-diameter wells is cheaper, observation wells with inner diameters ranging from 50 to 150 mm are common. Hydraulic rotary drilling, with bits ranging in diameter from 115 to 165 mm, is often used. The rotary method is faster than the percussion method in sedimentary formations except in formations containing cobbles, chert or boulders. Because the rock cuttings are removed from the hole in a continuous flow of the drilling fluid, samples of the formations can be obtained at regular intervals. This is done by drilling down to the sampling depth, circulating the drilling fluid until all cuttings are flushed from the system, and drilling through the sample interval and removing the cuttings for the sample. Experienced hydrogeologists and drillers can frequently identify changes in formation characteristics and the need for additional samples by keeping watch on the speed and efficiency of the drill.

The percussion-tool method is preferred for drilling creviced-rock formations or other highly permeable material. The normal diameter of the well drilled by percussion methods ranges from 100 to 200 mm to allow for the observation well casing to be 50 to 150 mm in diameter. The percussion-tool method allows the collection of samples of the excavated material from which a description of the geological formations encountered can be obtained.

In many cases, the aquifer under study is a confined aquifer separated by a much less permeable layer from other aquifers. Upper aquifers penetrated during drilling must be isolated from the aquifer under study by a procedure known as sealing (or grouting). The grout may be clay or a fluid mixture of cement and water of a consistency that can be forced through grout pipes and placed as required. Grouting and sealing the casing in observation wells are carried out for the following reasons:

(a) To prevent seepage of polluted surface water to the aquifer along the outside of the casing;
(b) To seal out water in a water-bearing formation above the aquifer under study;
(c) To make the casing tight in a drilled hole that is larger than the casing.

The upper 3 m of the well should be sealed with impervious material. To isolate an upper aquifer, the seal of impervious material should not be less than 3 m long extending above the impervious layer between the aquifers.

In consolidated rock formations, observation wells may be drilled and completed without casings. Figure I.6.2 shows a completed well in a rock formation. The drilled hole should be cleaned of fine particles and as much of the drilling mud as possible. This cleaning should be done by pumping or bailing water from the well until the water clears.

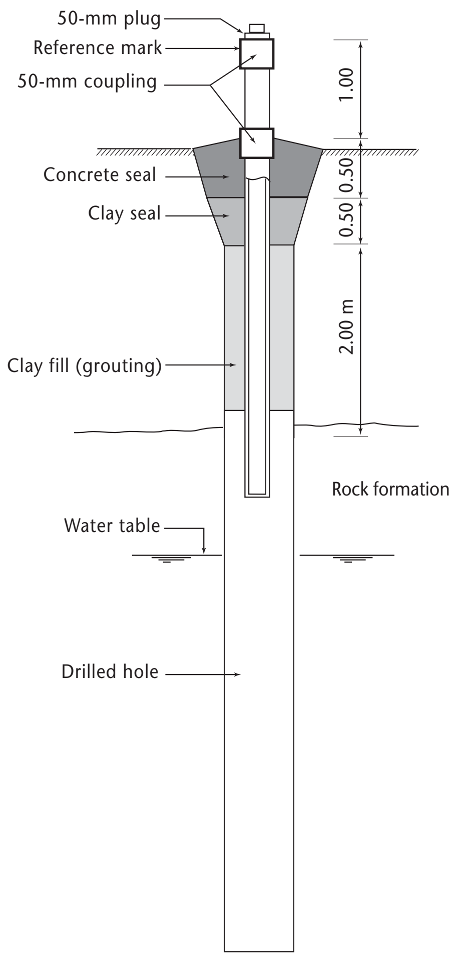


Figure I.6.2. Observation well in a rock formation

Casing is installed in wells in unconsolidated deposits. The main features of such an installation are shown in Figure I.6.3. It should be noted that:

(a) The normal diameter of the casing in observation wells is 50 mm;
(b) At the bottom of the hole, a blank length of casing (plugged at the lower end) is installed. This blank casing should be at least 3 m long and serves to collect sediment from the perforated part of the casing. This is referred to as the debris sump;
(c) A perforated or slotted length of casing, known as the strainer or screen, is secured to the debris sump and ensures free interchange of water between the aquifer and the observation well. The screen should be about 2 m long;
(d) The blank casing above the screen should be long enough to protrude above ground level by about 1 m. The top of this blank casing forms a convenient reference point for the datum of the observation programme;
(e) Centring spiders ensure proper positioning of the screen column in the drilled hole;
(f) In aquifers with fine or silty sand, the mesh jacket and slotted casing should be protected from clogging by fine material. Graded coarse material should be packed around the screen to fill the annular space between the screen and the wall of the drilled hole. In the case of a 150-mm hole and 50-mm casing pipe, the normal thickness of the gravel packing should be approximately 45 mm but should not be less than 30 mm thick. The material may be river gravel, ranging from 1 to 4 mm in diameter. The gravel should be placed through a guide pipe of small diameter, introduced into the space between the casing and the wall of the hole. The amount of gravel that is used should be sufficient to fill both the annular space and the bottom of the hole, that is, the whole length of the debris sump as well as the length of the screen and at least 500 mm of the casing above the perforation;
(g) At ground level, a pit should be excavated around the casing. The recommended dimensions of the pit are 800 x 800 mm at ground level going down as a cone with a lower base approximately 400 x 400 mm at a depth of 1 m. Clay grout should be placed around the casing to a depth of 2 m to make the casing tight in the drilled hole and to prevent seepage of polluted surface water into the aquifer. The pit should be filled partly by a clay seal and the upper part with concrete. The concrete should be poured to fill the pit and form a cone around the casing to drain precipitation and drainage water away from the well;
(h) The upper end of the protruding casing above the concrete cone should be closed for security purposes. Figure I.6.3 shows details of the installation of the well. The outer 50-mm plug is screwed to the casing by using a special tool, and the iron plug inside the casing can be lifted by the observer using a strong magnet.

The part of the casing extending above ground level should be painted a bright colour to make it easy to detect from a distance. Depth-to-water table is measured from the edge of the casing (after removal of plugs). This reference mark should be levelled to a common datum for the area under investigation.

Observation wells should be maintained by the agency responsible for the monitoring or investigation. The area around the well should be kept clear of vegetation and debris. A brass disc may be anchored in the concrete seal at ground level bearing the label “observation well” and the name of the agency or organization. This brass disc may also serve as a benchmark for survey purposes.

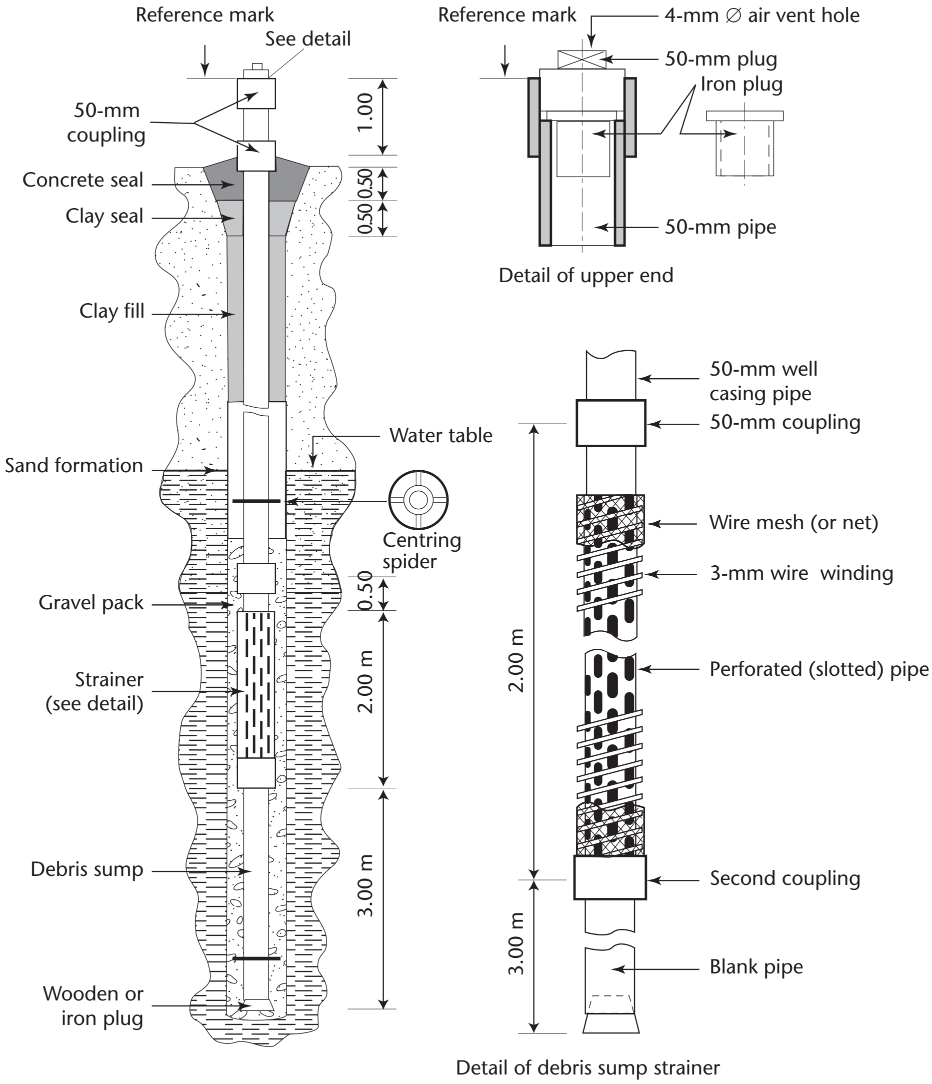


Figure I.6.3. Observation well in a sand formation

Should the protruding part of the well casing be replaced because of damage, then the levelling of the new reference mark is simplified by the proximity of the benchmark. Pre-existing wells that serve as observation wells should be maintained and labelled in the same manner as wells drilled specifically as observation wells.

In the area under study, several aquifers at different levels may be separated by impervious layers of different thicknesses. In such cases, it is advisable to observe the following routine (Figure I.6.4):

(a) A large diameter well should be drilled, by the percussion-tool method, until the lowest aquifer is penetrated;
(b) A small-diameter observation pipe with a proper screen is installed in the lowest aquifer;
(c) The outer casing is lifted to reach the bottom of the impervious layer above this aquifer. A gravel pack is then placed around the screen of the observation pipe and the top end of the lower aquifer is then sealed by cement or other suitable grout;
(d) Another small-diameter observation pipe with a screen is then lowered to the next higher aquifer that is again gravel packed and sealed off by grouting from the aquifer lying above it;
(e) Steps (c) and (d) are repeated for each additional aquifer that is penetrated.

In this case, the sealing of each of the aquifers should be done very carefully to prevent damage to the water-bearing formation either by the interchange of water with different chemical properties or by loss of artesian pressure. If the geology of the area is well known and the depth to each of the aquifers can be predicted, it may be advisable to drill and construct a separate well in each aquifer.

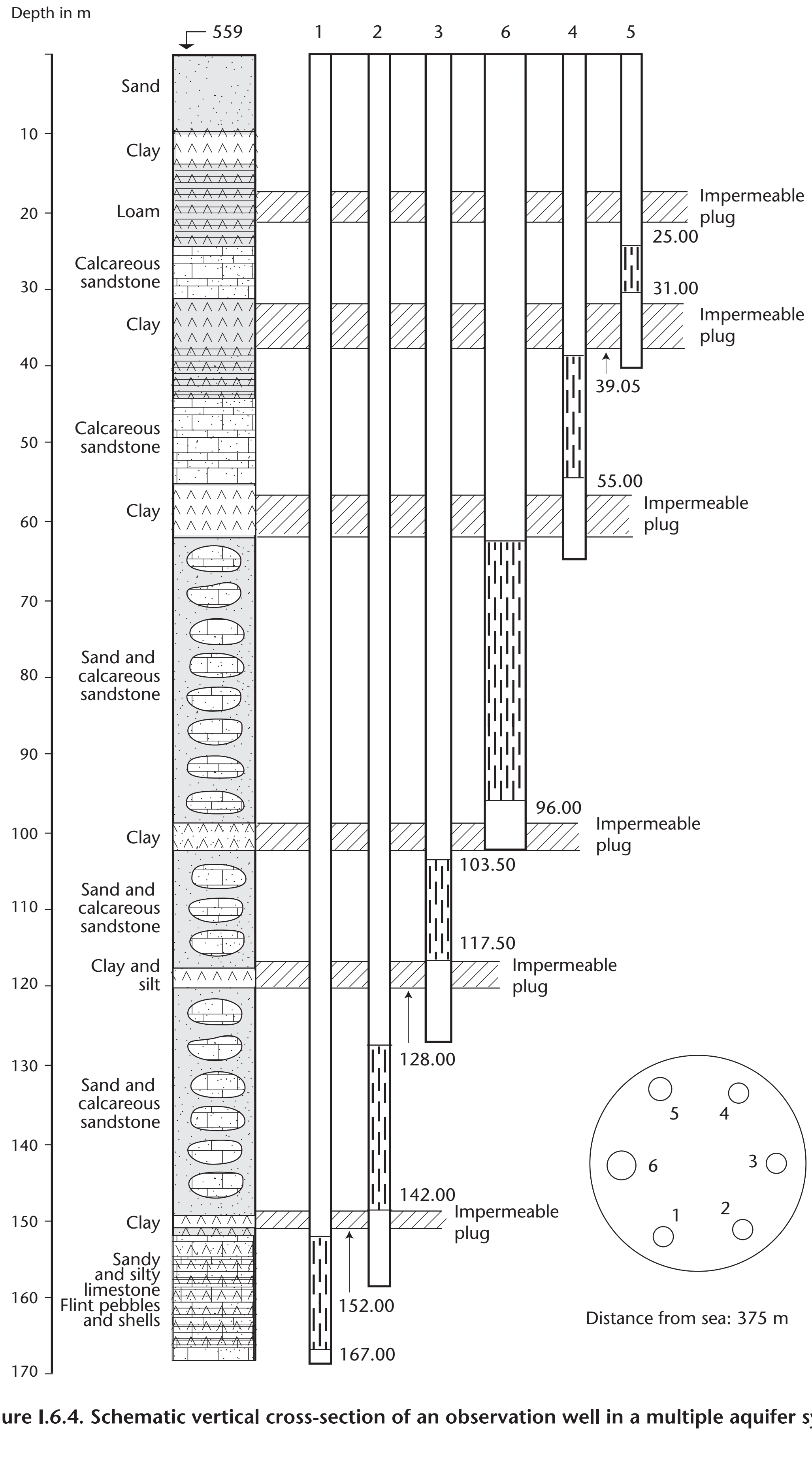


Figure I.6.4. Schematic vertical cross-section of an observation well in a multiple aquifer system

Such boreholes are spaced only a few metres apart. This procedure may prove to be more economical.

Where privately owned pumping wells are incorporated into the observation network, arrangements could be made for such wells to be maintained by the owners.

6.3.2 Testing of observation wells

The response of an observation well to water-level changes in the aquifer should be tested immediately after the construction of the well. A simple test for small-diameter observation wells is performed by observing the recharge of a known volume of water injected into the well, and measuring the subsequent decline of water level. For productive wells, the initial slug of water should be dissipated within three hours to within 5 mm of the original water level. If the decline of the water level is too slow, the well must be developed to remove clogging of the screen or slots and to remove as much as possible of the fine materials in the formation or the pack around the well. Development is achieved by alternately inducing movement of the groundwater to and from the well.

After cleaning the well, the depth from the reference mark to the bottom of the well should be measured. This measurement, compared with the total length of casing, shows the quantity of sediment in the debris sump. This test should be repeated occasionally in observation wells to check the performance of the screen. If the measurement of the bottom of the well shows that debris fills the whole column of the sump and the screen, then the water level in the well might not represent the true potentiometric head in the aquifer. If the reliability of an observation well is questionable, there are a number of technical procedures that can be used to make the well function adequately again.

6.3.3 Sealing and filling of abandoned wells

Observation wells and pumping wells may be abandoned for the following reasons:
(a) Failure to produce either the desired quantity or quality of water;
(b) Drilling of a new well to replace an existing one;
(c) Observation wells that are no longer needed for investigative purposes.

In all these cases, the wells should be closed or destroyed in such a way that they will not act as channels for the interchange of water between aquifers when such interchange will result in significant deterioration of the quality of water in the aquifers penetrated.

Filling and sealing of an abandoned well should be performed as follows:
(a) Sand or other suitable inorganic material should be placed in the well at the levels of the formations where impervious sealing material is not required;
(b) Impervious inorganic material must be placed at the levels of confining formations to prevent water interchange between different aquifers or loss of artesian pressure. This confining material must be placed at a distance of at least 3 m in either direction (below and above the line of contact between the aquifer and the aquiclude);
(c) When the boundaries of the various formations are unknown, alternate layers of impervious and previous material should be placed in the well;
(d) Fine-grained material should not be used as fill material for creviced or fractured rock formations. Cement or concrete grout should be used to seal the well in these strata. If these formations extend to considerable depth, alternate layers of coarse fill and concrete grout should be used to fill the well;
(e) In all cases, the upper 5 m of the well should be sealed with inorganic impervious material.

6.4 GROUNDWATER-LEVEL MEASUREMENTS AND OBSERVATION WELL NETWORKS [HOMS C65, E65, G10]

6.4.1 Instruments and methods of observation

Direct measurement of groundwater levels in observation wells can be accomplished either manually or with automatic recording instruments. The following descriptions relate to principles of measurement of groundwater levels. The references include descriptions of certain instruments.

6.4.1.1 Manually operated instruments

The most common manual method is by suspending a weighted line (for example, a graduated flexible steel or plastic-coated tape or cable) from a defined point at the surface, usually at the well head, to a point below the groundwater level. On removal of the tape, the position of the groundwater level is defined by subtracting the length of that part of the tape which has been submerged from the total length of the tape suspended in the well. This wetted part can be identified more clearly by covering the lower part of the tape with chalk before each measurement. Colour changing pastes have been used to indicate submergence below water, although any such substance containing toxic chemicals should be avoided. Several trial observations may have to be made unless the approximate depth-to-water surface is known before measurement. As depth-to-water level increases and the length of tape to be used increases, the weight and cumbersome nature of the instrument may be difficult to overcome. Depths-to-water surface of up to 50 m can be measured with ease and up to 100 m or more with greater difficulty. At these greater depths, steel tapes of narrower widths or lightweight plastic-coated tapes can be used. Depths-to-water level can be measured to within a few milimetres but the accuracy of measurement by most methods is usually dependent on the depth.

Inertial instruments have been developed so that a weight attached to the end of a cable falls at constant velocity under gravity from a portable instrument located at the surface. On striking water, a braking mechanism automatically prevents further fall. The length of free cable, equivalent to the depth-to-water level, is noted on a revolution counter. The system is capable of measurement within 1 cm, although with an experienced operator this may be reduced to 0.5 cm.

The double-electrode system employs two small adjacent electrodes incorporated into a single unit of 10 to 20 cm in length at the end of the cable. The system also includes a battery and an electrical current meter. Current flows through the system when the electrodes are immersed in water. The cable must have negligible stretch and plastic-coated cables are preferred to rubber sheathed cables. The cable is calibrated with adhesive tape or markers at fixed intervals of 1 or 2 m. The exact depth-to-water level is measured by steel rule to the nearest marker on the cable. Measurement of water level down to about 150 m can be undertaken with ease and up to 300 m and more, with some difficulty. The limits to depths of measurement are essentially associated with the length of the electrical cable, the design of the electrical circuitry, the weight of the equipment (particularly the suspended cable), and the effort in winding-out and winding-in the cable. The degree of accuracy of measurement depends on the operator's skill and on the accuracy with which markers are fixed to the cable. The fixed markers should be calibrated and the electrical circuitry should be checked at regular intervals, preferably before and after each series of observations. This system is very useful when repeated measurements of water levels are made at frequent intervals during pumping tests.

In deep wells that require cable lengths in the order of 500 m, the accuracy of the measurement is approximately ±15 cm. However, measurements of change in water level, where the cable is left suspended in the wells with the sensor near the water table, are reported to the nearest millimetre.

The electrochemical effect of two dissimilar metals immersed in water can be applied to manual measuring devices. This results in no battery being required for an electrical current supply. Measurable current flow can be produced by the immersion in most groundwaters either of two electrodes (for example, magnesium and brass) incorporated into a single unit, or of a single electrode (magnesium) with a steel earth pin at the surface. Because of the small currents generated, a microammeter is required as an indicator. The single-electrode system can be incorporated into a graduated steel tape or into a plastic-coated tape with a single conductor cable assembly. The accuracy of measurement depends upon the graduations on the tape, but readings to within 0.5 cm can be readily achieved.

A float linked to a counterweight by a cable that runs over a pulley can be installed permanently at an observation well. Changes in water level are indicated by changes in the level of the counterweight or of a fixed marker on the cable. A direct reading scale can be attached to the pulley. The method is generally limited to small ranges in fluctuation.

When artesian groundwater flows at the surface, an airtight seal has to be fixed to the well head before pressure measurements can be undertaken. The pressure surface (or the equivalent water level) can be measured by installing a pressure gauge (visual observations or coupled to a recording system) or, where practicable, by observing the water level inside a narrow-diameter extension tube made of glass or plastic, fitted through the seal directly above the well head. Where freezing may occur, oil or an immiscible antifreeze solution should be added to the water surface.

All manual measuring devices require careful handling and maintenance at frequent intervals so that their efficiency is not seriously impaired. The accurate measurement of groundwater level by manual methods depends on the skill of a trained operator.

6.4.1.2 Automatic recording instruments

Many different types of continuous, automatically operated water-level recorders are in use. Although a recorder can be designed for an individual installation, emphasis should be placed on versatility. Instruments should be portable, easily installed, and capable both of recording under a wide variety of climatic conditions and of operating unattended for varying periods of time. They should also have the facility to measure ranges in groundwater fluctuation at different recording speeds by means of interchangeable gears for time and water-level scales. Thus, one basic instrument, with minimum ancillary equipment, can be used over a period of time at a number of observation wells and over a range of groundwater fluctuations.

Experience has shown that the most suitable analogue recorder currently in operation is float actuated. The hydrograph is traced either onto a chart fixed to a horizontal or vertical drum or onto a continuous strip chart. To obtain the best results with maximum sensitivity, the diameter of the float must be as large as practicable with minimum weight of supporting cable and counterweight. As a generalization, the float diameter should not be less than about 12 cm, although modifications to certain types of recorders permit using smaller-diameter floats. The recording drum or pen can be driven by a spring or by an electrical clock. The record can be obtained by pen or by weighted stylus on specially prepared paper. By means of interchangeable gears, the ratio of drum movement to water-level fluctuation can be varied and reductions in the recording of changes in groundwater levels commonly range from 1:1 up to 1:20. The tracing speed varies according to the make of instrument, but the gear ratios are usually so adapted that the full width of a chart corresponds to periods of 1, 2, 3, 4, 5, 16 or 32 days. Some strip-chart recorders can operate in excess of six months.

Where float-actuated recorders have lengths of calibrated tape installed, a direct reading of the depth (or relative depth) to water level should be noted at the beginning and at the end of each hydrograph when charts are changed. This level should be checked against manual observations at regular intervals. The accuracy of reading intermediate levels on the chart depends primarily upon the ratio of drum movement to groundwater-level fluctuations, and therefore is related to the gear ratios.

The continuous measurement of groundwater level in small-diameter wells presents problems because a float-actuated system has severe limitations as the diameter of the float decreases. Miniature floats or electrical probes of small diameter have been developed to follow changes in water level. The motivating force is commonly provided by a servo-mechanism (spring or electrically driven) located in the equipment at the surface. The small float is suspended in the well on a cable stored on a motor-driven reel that is attached to the recorder pulley. In the balanced (equilibrium) position, the servo-motor is switched off. When the water table in the well moves down, the float remains in the same position and its added weight unbalances the cable (or wire), causing the reel to move and, by this small movement, causing an electrical contact to start the small motor. The reel operated by this motor releases the cable until a new equilibrium is reached, and the motor is switched off. When the water level in the well rises, the cable is retrieved on the reel until the new equilibrium is reached. This movement of the cable on or off the reel actuates the pen of the recorder, and water-level fluctuations are recorded. The servo-motor, which rotates the cable reel, may be activated by an electrical probe at the water table in the well. This attachment consists of a weighted probe suspended in the well by an electric cable stored on the motor-driven reel of the water-level recorder. Water-level fluctuations in the well cause a change in pressure that is transmitted by a membrane to the pressure switch in the probe. The switch actuates the reel motor, and the probe is raised or lowered, as required, until it reaches a neutral position at the new water level. Float and float-line friction against the well casing can affect the recording accuracy of water-level recorders, especially in deep wells.

The largest error is caused by float line drag against the well casing. A small-diameter float may be provided with sliding rollers (fixed at both ends of the float) to reduce friction against the casing. Round discs (spiders) with small rollers attached to the cable at 10-m intervals keep the cable away from the well casing and significantly reduce friction. Figure I.6.5 shows some details of this device. The sensitivity of water-level recorders with attachments for small-diameter floats may be 6 mm of water-level movement, but the switching mechanism of the float may not be this sensitive. The accuracy of the mechanism is decreased by weak batteries. To avoid this effect, the batteries should be replaced after a maximum of 60 to 90 days of normal use.

An alternative approach is an electrode suspended in an observation well at a fixed distance above the water level. At specified time intervals, the probe electrically senses the water level and the movement occurs by a servo-mechanism at the surface. The depth-to-water level is then recorded. This system can be adapted to various recording systems.

Although these instruments have particular value in small-diameter wells, they can be installed in wells of any diameter greater than the working diameter of the probe.

Analogue-to-digital stage recorders used for stream discharge measurements can be readily adapted to the measurement of groundwater levels.

Automatic recording instruments require comprehensive and prompt maintenance otherwise records will be lost. Simple repairs can be undertaken on the site, but for more serious faults, the instrument should be replaced and repairs should be undertaken in the laboratory or workshop. Adequate protection from extremes of climatic conditions, accidental damage and vandalism should be provided for these instruments. Clockwork is particularly susceptible to high humidity, thus adequate ventilation is essential, and the use of a desiccant may be desirable under certain conditions.

In some research projects, instruments have been designed to measure fluctuations in groundwater level by more sophisticated techniques than those described above, such as capacitance probes, pressure transducers, strain gauges, and sonic and high-frequency wave reflection techniques. At present, these instruments are expensive when compared with float-actuated recorders, have limitations in application, particularly in the range of

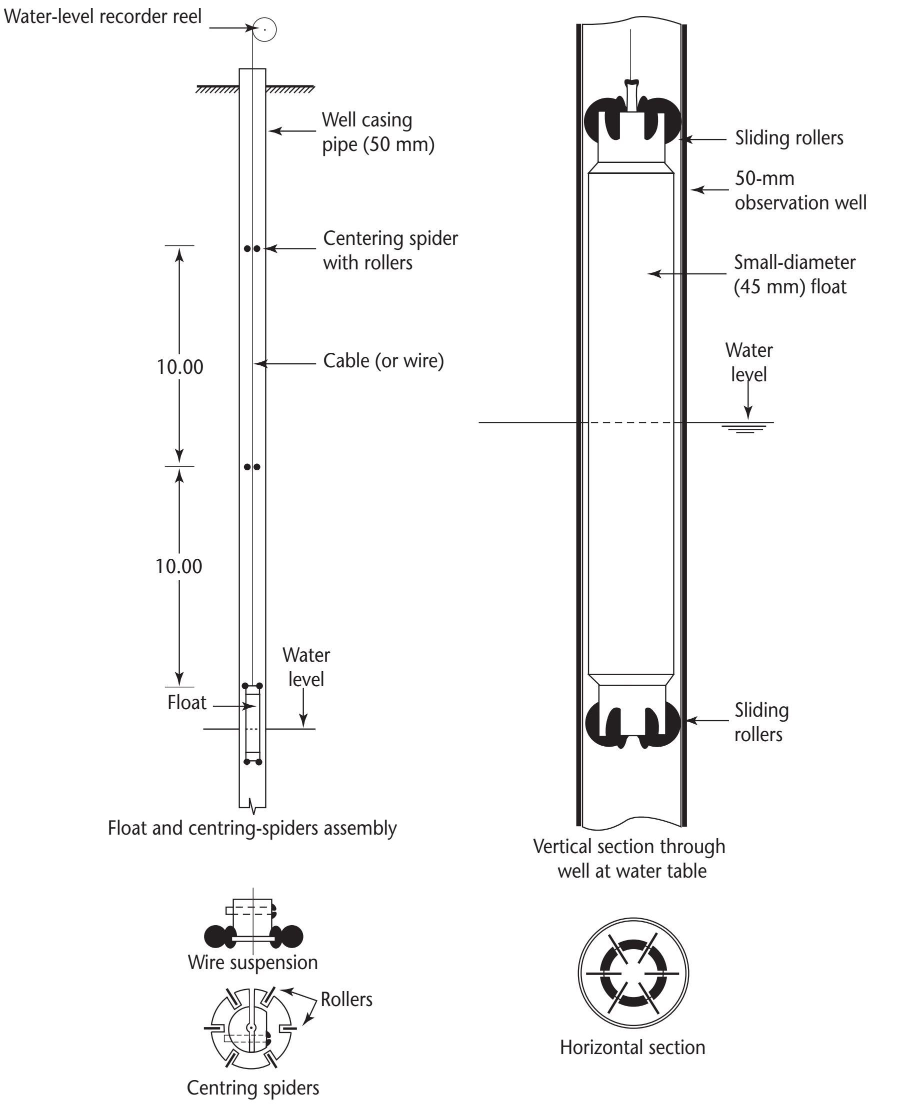


Figure I.6.5. Small-diameter float with sliding rollers in an observation well

groundwater fluctuations, and commonly require advanced maintenance facilities. Float-actuated systems are considered more reliable and more versatile than any other method, although future developments in instrument techniques in the sensor, transducer and recording fields may provide other instruments of comparable or better performance at competitive costs.

6.4.1.3 Observation well network

An understanding of the groundwater conditions relies on the hydrogeological information available; the greater the volume of this information the better the understanding as regards the aquifers, water levels, hydraulic gradients, flow velocity and direction and water quality, among others. Data on potentiometric (piezometric) heads and water quality are obtained from measurements at observation wells and analysis of groundwater samples. The density of the observation well network is usually planned on the data requirement but in reality is based on the resources available for well construction. Drilling of observation wells is one of the main costs in groundwater studies. The use of existing wells provides an effective low-cost option Therefore, in the development of an observation network, existing wells in the study area should be carefully selected and supplemented with new wells drilled and specially constructed for the purposes of the study.

6.4.1.4 Water-level fluctuations

Fluctuations in groundwater levels reflect changes in groundwater storage within aquifers. Two main groups of fluctuation can be identified: long-term, such as those caused by seasonal changes in natural replenishment and persistent pumping, and short-term, for example, those caused by the effects of brief periods of intermittent pumping and tidal and barometric changes. Because groundwater levels generally respond rather slowly to external changes, continuous records from water-level recorders are often not necessary. Systematic observations at fixed time intervals are frequently adequate for the purposes of most national networks. Where fluctuations are rapid, a continuous record is desirable, at least until the nature of such fluctuations has been resolved.

6.4.1.5 Water-level maps

A useful approach to organize and coordinate water-level measurements from a network of observation wells is to produce an accurate map of well locations and then to contour the water-level data available at each well. Two types of maps can be produced, based on either the depth-to-water level measured in a well from the land surface or the elevation of the water level in the well relative to an established datum, such as sea level. Generally, these maps are produced on a single aquifer basis using data collected on a synoptic basis for a discrete period of time, to the extent possible. Seasonal fluctuations in water levels, changes in water levels over a period of years as a result of pumping, and similar effects can cause disparate variations if a mixture of data is used.

6.4.1.5.1 *Depth-to-water maps*

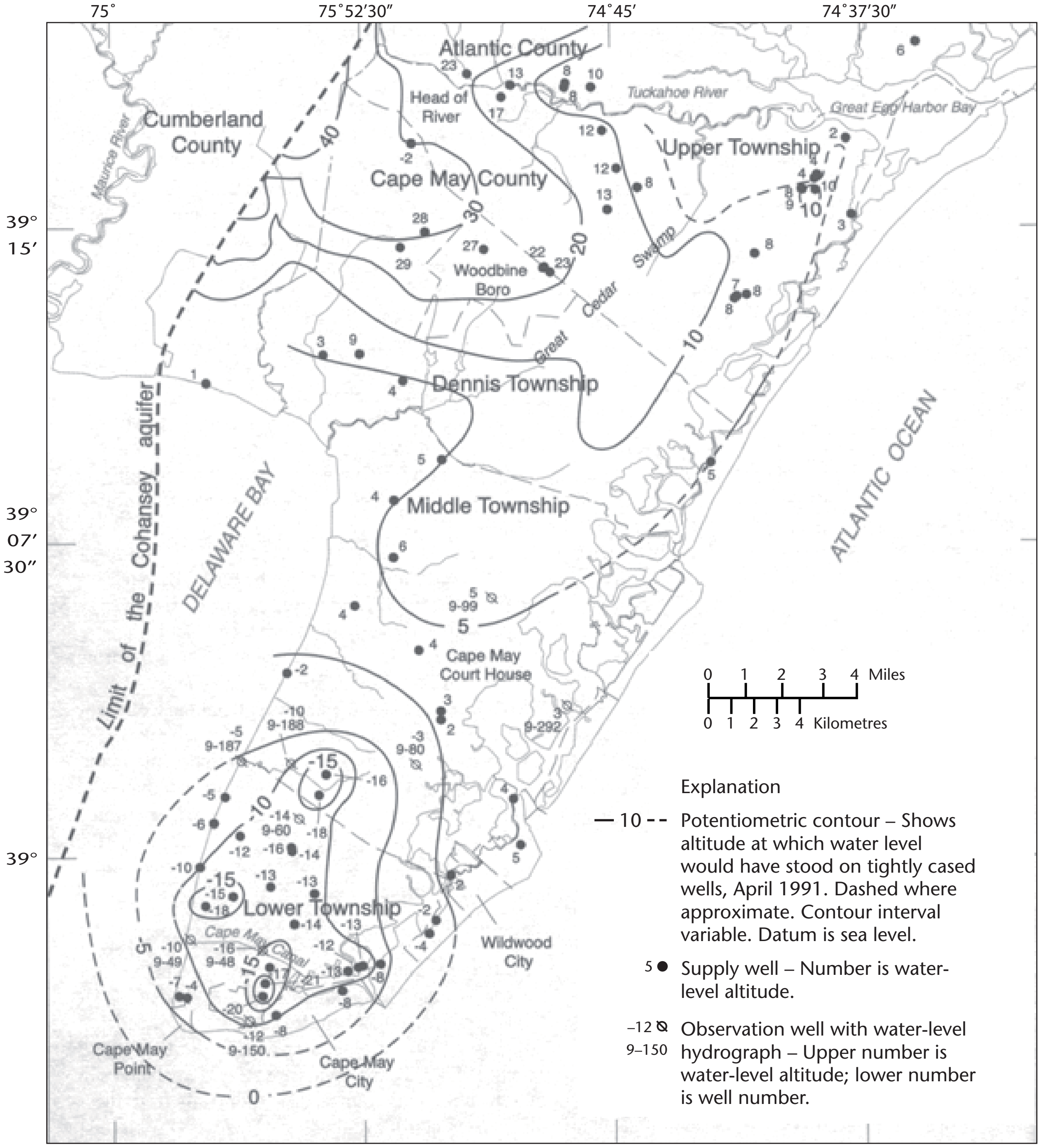
The simplest map to produce is based on the measurement of the depth-to-water level in a well relative to land surface. This is referred to as a depth-to-water map. Maps of this type provide an indication as to the necessary depth to drill to encounter water, which can be useful in planning future resource development projects. A map based on the difference in depth to water between two measurement periods could be used to show, for example, the areal variation of seasonal fluctuations. A significant limitation of a depth-to-water map is that it cannot be used to establish the possible direction of groundwater flow because of the independent variation of topographic elevation.

6.4.1.5.2 *Potentiometric (Piezometric) surface maps/water table maps, potentiometric cross-sections*

A water-level map based on the elevation of the water level in a well relative to a common datum, such as sea level, is referred to as a potentiometric surface map (Figure I.6.6). When produced for the water table or the surficial aquifer, this map may be referred to as a water table map. This type of map is more difficult to produce than a depth-to-water map because it requires accurate elevation data for the measuring point at each observation well. Each depth-to-water measurement collected must be subtracted from the elevation of the measuring point relative to the datum to produce the necessary data. A significant benefit of this type of map is that it can be used to infer the direction of groundwater flow in many cases.

The accuracy of the map is dependent on the accuracy of the measuring point elevations. The most accurate maps will be based on elevations that have been established using formal, high-order land-surveying practices. This can entail substantial effort and expense. Several alternatives exist. These are the use of elevations determined from topographic maps, if they exist for the study area, or the use of an altimeter or GPS unit to provide elevation information. Any report showing a potentiometric surface map must have an indication of the source and accuracy of the elevation data.

Maps portray information in two spatial dimensions. As groundwater flows in three dimensions, another view is required to understand the potentiometric data in all directions. With potentiometric surface data from multiple aquifers or depths at each or many data sites of an observation well network it is possible to produce potentiometric cross-sections (Figure I.6.7). Potentiometric cross-sections are an accurately scaled drawing of well locations along a selected transect indicating depth on the vertical axis and lateral distance on the horizontal axis. A particular well's water level is plotted with respect



Based on United States Geological Survey digital data, 1:100 000, 1983. Universal Transverse Mercator Projection, Zone 18.

Figure I.6.6. Example of a potentiometric surface map (Lacombe and Carleton, 2002) to the depth axis. It is customary to also indicate a well's open interval on the diagram. These cross-sections can show the relative differences in water levels between aquifers and can be very useful in determining the vertical direction of groundwater flow.

6.4.1.6 Well discharge measurements

Pumping wells can have a significant effect on groundwater flow and levels. The measurement of a pumping well's discharge is important to facilitate comparisons of drawdown effects and for quantitative analysis. The common methods of measurement include the timed fill of a calibrated volume, flow meters and orifice discharge measurements (American Society for Testing and Materials International: ASTM D5737-95, 2000). The discharge of a pumping well will vary with changes in groundwater level. This may require repeated measurements to keep track of the rate. When a pump is turned on, the water level in a well drops accordingly, thereby causing the discharge to vary. Stability in pumping rate is generally reached in a matter of minutes or hours. Water-level changes that could affect pumping rate can also occur as a result of recharge from precipitation or changes in pumping of nearby wells. Changes in the configuration of the discharge plumbing, such as pipe length or diameter to a point of free discharge, can also have an effect and should be avoided. These flow measuring procedures can also be applied to measuring the discharge of a naturally flowing well.

6.4.1.6.1 *Calibrated volume*

The simplest method of determining the rate of discharge from a pumping well is by measuring the time the pumped discharge takes to fill a calibrated volume. Dividing that volume by the time yields the unit pumping rate. The accuracy of the measurement is dependent on the accuracy of the time measurement and the logistics of filling the calibrated volume. For relatively low pumping, this measurement is easily handled using a bucket or drum with calibration marks. However, at relatively high discharge rates, a measurement of this type may require some logistical planning in order to direct the discharge into an appropriate vessel or container for measurement. The force of the discharge stream or the presence of entrained air can complicate the situation.

6.4.1.6.2 *Flow meters*

A variety of mechanical, electrical and electronic meters have been developed to measure fluid flow inside a pipe. Many of these can be easily used to measure the rate of discharge from a pumped well. Some meters provide an instantaneous discharge reading while others compile a totalized reading of flow. Either type can be used. Some versions have

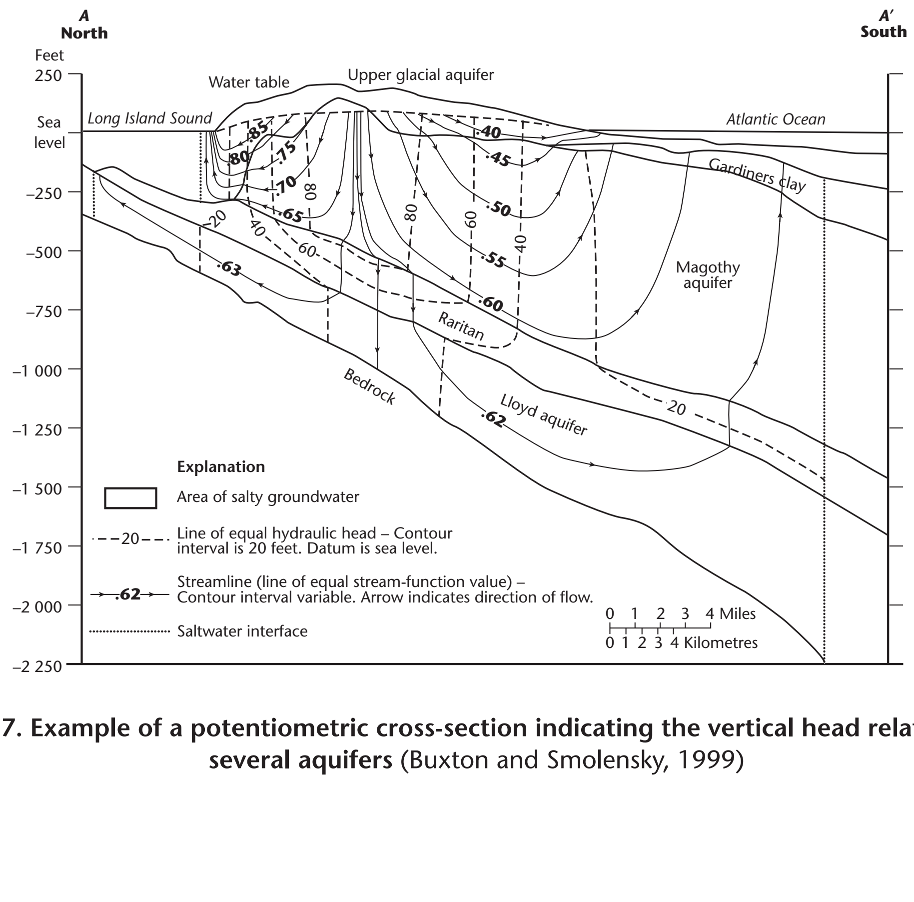


Figure I.6.7. Example of a potentiometric cross-section indicating the vertical head relation between several aquifers (Buxton and Smolensky, 1999) the ability to interface with electronic data logging equipment. The appropriate instructions from the manufacturer should be followed to ensure an accurate measurement. Flow meter readings can be sensitive to the presence of turbulence in the flow. Operational instructions may require that a prescribed length of straight pipe precede the meter to minimize turbulence effects. Additionally, a full-pipe condition is required for most meters. When a relatively large-diameter pipe serves as a conduit for a relatively small discharge rate, the pipe may not be entirely filled with water. To maintain a full-pipe condition, a valve positioned downstream of the meter can be partially closed. Entrained air or sediment in the flow can possibly affect the accuracy of the reading and in the case of sediment, can possibly damage the sensing equipment.

6.4.1.6.3 *Orifice discharge*

Another common method for measuring the discharge from a pumped well is the use of a free discharge pipe orifice. An orifice is an opening in a plate of specified diameter and beveled-edge configuration that is fixed, usually by a flange, over the end of a horizontal discharge pipe (Figure I.6.8). The diameter of the orifice should be smaller than the diameter of the pipe. The water flowing through the discharge pipe is allowed to freely exit through the orifice. As the orifice somewhat restricts the flow, a back pressure results that is proportional to the flow. This pressure is measured, usually by direct measurement of a manometer tube, located about three pipe diameters upstream of the orifice and at the centre line of the pipe. The measured pressure value, the discharge pipe diameter and the orifice diameter are used to enter an “orifice table” to determine the flow. These tables and the specific requirements for the design of the discharge pipe and orifice can be found in ISO 5167-2 (2003*b*).

6.4.1.6.4 *Specific capacity*

A useful index to facilitate a comparison of water-level drawdown and discharge rates among wells is specific capacity. This parameter is defined as the well’s steady-state discharge rate divided by the drawdown in the pumped well from its non-pumping state to the steady-state pumping level ($m^3\ s^{-1}m^{-1}$).

6.4.1.7 Drawdown from a pumped well; cone of depression

The movement of water from an aquifer into a pumped well is impeded by frictional resistance with the aquifer matrix. This resistance results in a lowering or decline in the water level in a well being pumped and in the adjacent parts of the aquifer. This decline is referred to as drawdown. Drawdown is defined as the change in water level from a static pre-pumping level to a pumping level. Water-level decline resulting from pumpage diminishes non-linearly with distance away from the pumped well. The resulting shape is referred to as a cone of depression. The drawdown and resulting cone of depression in an unconfined aquifer is the result of gravity drainage and desaturation of part of the aquifer in the vicinity of the well (Figure I.6.9 (left)). In a confined aquifer, the cone of depression is manifested as a decline in the potentiometric (piezometric) surface, but does not represent a desaturation of the aquifer (Figure I.6.9 (right)). The relation between pumping rate, water-level decline and distance from the well is a function of the prevailing permeability of the aquifer material and the availability of sources of recharge.

6.5 AQUIFER AND CONFINING-BED HYDRAULIC PROPERTIES

Quantitative analysis of groundwater flow involves understanding the range and variability of key hydraulic parameters. Many data-collection networks and surveys are organized to collect data for the purpose of determining aquifer and confining bed properties.

6.5.1 Hydraulic parameters

The movement of groundwater is controlled by certain hydraulic properties, the most important being the permeability. For the study of the movement of water in earth materials the parameter for permeability is calculated assuming the physical properties (viscosity, etc.) of water and is termed hydraulic conductivity. Hydraulic conductivity is defined as the volume of water that will move in a unit time under a unit hydraulic gradient through a unit area, which results in units of velocity (distance per time). The typical ranges of hydraulic conductivity for common rock and sediment types are shown on Figure I.6.10. A related term is transmissivity, which is defined as the hydraulic conductivity multiplied by the aquifer thickness. The difference between the two are that hydraulic conductivity is a unit property, whereas transmissivity pertains to the entire aquifer.

Storage coefficient is defined as the volume of water that an aquifer releases from or takes into storage

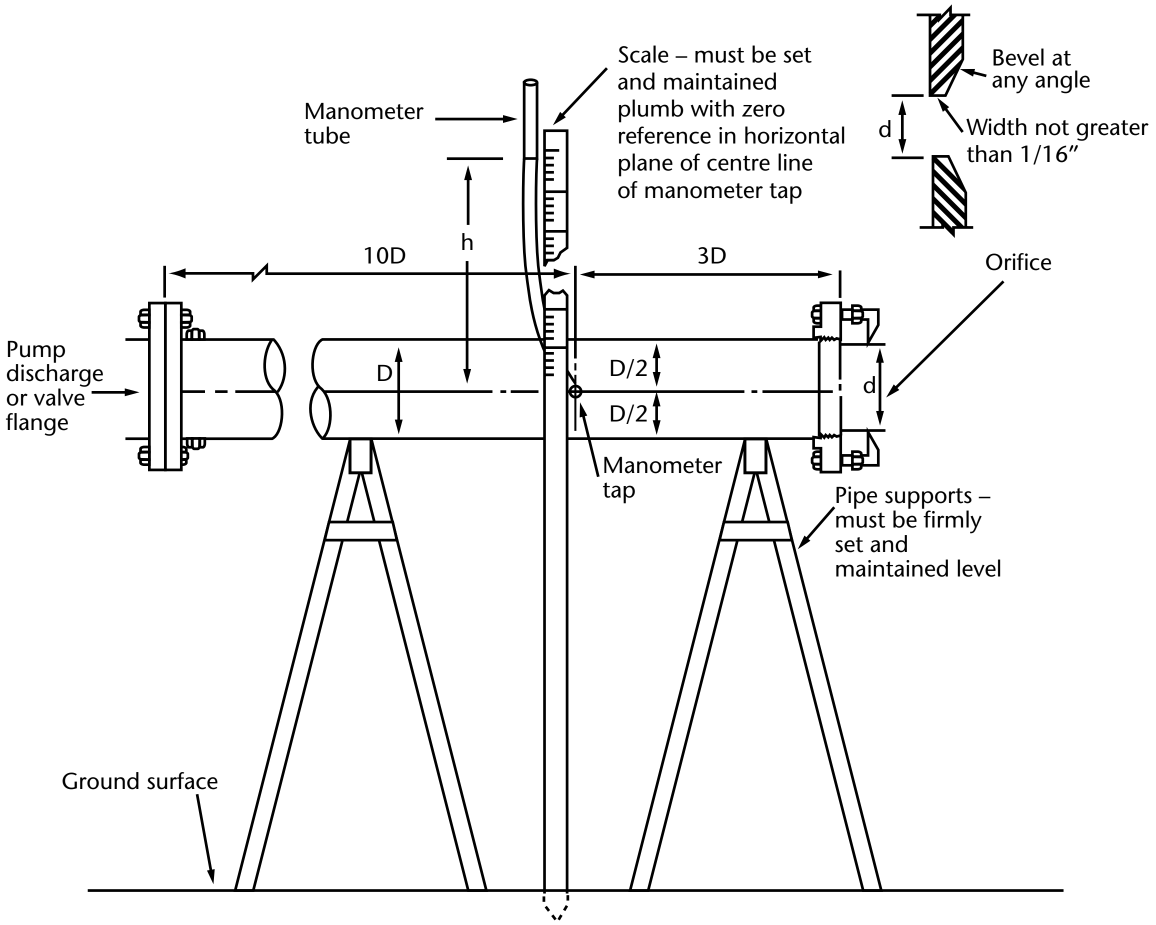


Figure I.6.8. Schematic diagram of how the free discharge orifice is set up for measuring discharge from a pumped well (United States Department of the Interior, 1977)

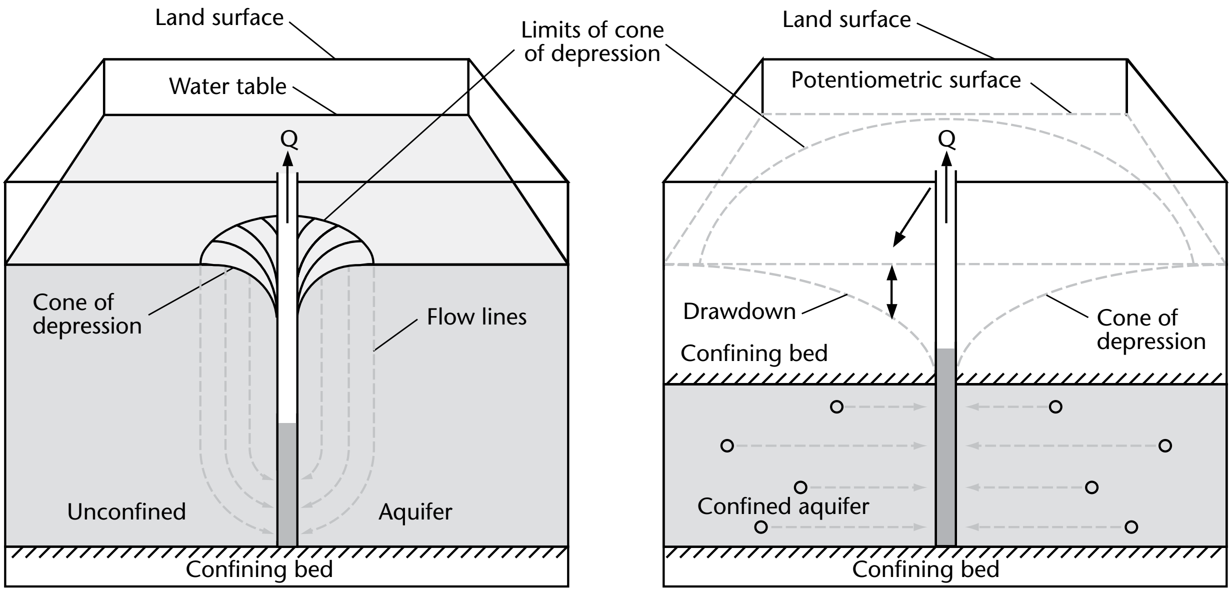


Figure I.6.9. Drawdown from a pumped well in (left) an unconfined aquifer and (right) in a confined aquifer (Heath, 1983)

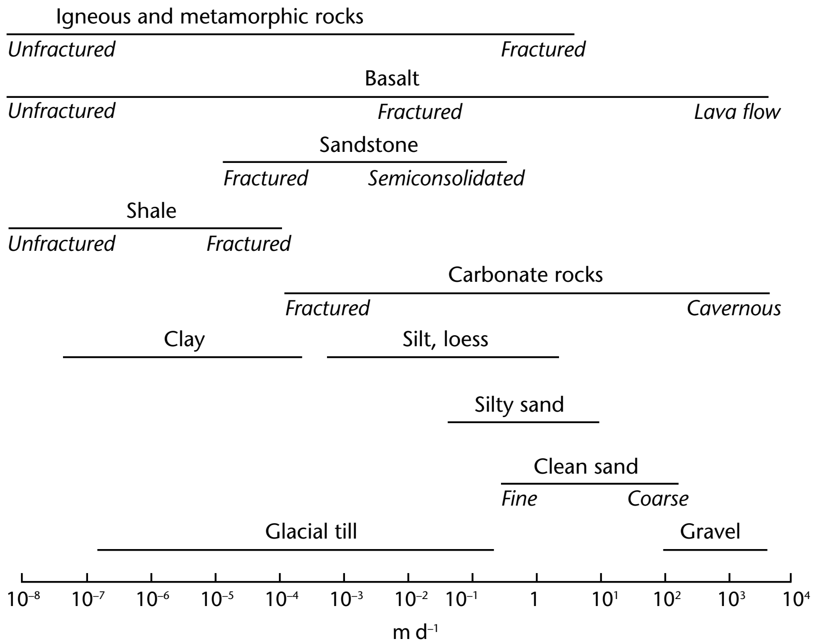


Figure I.6.10. Hydraulic conductivity of common rock and sediment types (Heath, 1983)

per unit surface area of the aquifer per unit change in head. Storage coefficient is a dimensionless parameter. For an unconfined aquifer, the storage coefficient is essentially derived from the yield by gravity drainage of a unit volume of aquifer, and typically ranges from 0.1 to 0.3 in value. For a confined aquifer, where saturation remains full, the storage results from the expansion of water and from the compression of the aquifer. The storage coefficient for a confined aquifer is therefore usually several orders of magnitude smaller than for an unconfined aquifer, typically ranging from 0.00001 to 0.001 in value.

Hydraulic conductivity and storage coefficient can be determined for confining units as well as aquifers. The differentiation of an aquifer from a confining unit is relative. For a given area, aquifers are considered to have hydraulic conductivities that are several orders of magnitude larger than confining units.

6.5.2 Overview of common field methods to determine hydraulic parameters

The determination of the hydraulic conductivity and storage coefficient specific to a particular aquifer or confining unit is generally accomplished through tests conducted in the field, referred to as aquifer or pumping tests. These aquifer tests are devised to measure the drawdown resulting from pumping or a similar hydrological stress and then to calculate the hydraulic parameters. The magnitude and timing of drawdown related to a specific test is directly related to the hydraulic conductivity and storage coefficient, respectively.

6.5.2.1 Aquifer (pumping) tests

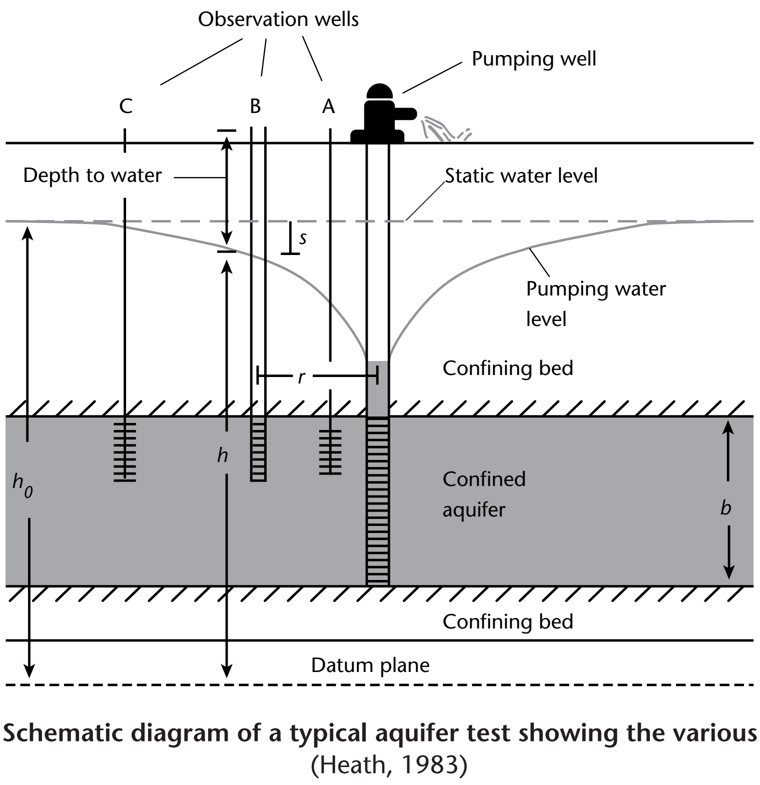
The general aim of an aquifer test is to determine hydraulic parameters where pumping is controlled and generally held constant and water levels in the pumped well and nearby observation wells are measured. Figure I.6.11 shows a schematic diagram of the set-up of a typical test of a confined aquifer of thickness, b. Three observation wells, labelled A, B and C, are located at various radii (r at well B) from the pumped well. The pumping, of known discharge, causes a cone of depression in the aquifers potentiometric (piezometric) surface to form which results in a drawdown, s, measured at well B, which is the difference between the initial head, h_0, and the pumping head, h. Water-level data in each well including the pumping well are collected prior to the start of pumping to establish the pre-test static water level, and thereafter throughout the test. The pump discharge is also monitored.

Aquifer tests typically are run from 8 hours to a month or longer, depending on the time required to achieve a steady pumping water level. When the pump is turned on, water levels will drop. The largest drawdown will be in the pumped well with drawdown decreasing non-linearly with distance away from the pumped well and increasing non-linearly with time. The observed values are the changing drawdown with time. This is referred to as a transient test, because of the changing drawdown with time. The data are generally plotted in two ways, as either log-log or semi-log graphs of distance and drawdown, or time and drawdown. The distance drawdown plot is for data from all wells for a particular instant in time, whereas the time-drawdown plot is for all data collected at one well. Generally, the analysis of the test data proceeds by either a manual, graphically based method or through the use of a computer program for aquifer-test analysis. The manual, graphically based method relies on an approach where the data plots are overlaid and matched to established "type curves" to calculate a solution for hydraulic conductivity and storage coefficient. The multiple plots are analysed individually and an average or consensus value for the test is determined.

It is beyond the scope of this Guide to explain in detail the exact data collection and analysis approach because there are many variants of the procedure. The variants result from a wide range of factors that can substantially affect the operation of the test and the specific analysis procedure, such as whether the test is transient or steady state, run with many observation wells or one, whether flow (leakage) to the tested aquifer will be considered from adjacent aquifers or confining units, and whether the aquifer is confined or unconfined. The practitioner is directed to Walton (1996), Kruseman and others (1994) and Reed (1980), for both an overview of the many common methods and a detailed description of the analysis techniques. Additionally, standards for conducting and analysing aquifer tests have been developed by the International Organization for Standardization (ISO 14686, 2003*a*) and the American Society for Testing and Materials International (ASTM D4106-96, 2002). An example of spreadsheet-formulated aquifer test analysis is presented by Halford and Kuniansky (2002).

6.6 RECHARGE AND DISCHARGE, SOURCES AND SINKS IN A GROUNDWATER SYSTEM

Recharge and discharge are the pathways by which water enters and leaves the groundwater system. Understanding and quantifying these pathways are key to understanding the nature of the whole groundwater system and being able to predict potential changes. The significant sources of recharge are from precipitation and leakage from surface water bodies, such as streams, rivers, ponds and lakes. The significant sources of discharge are leakage to surface water bodies, such as streams, rivers, ponds, lakes and oceans; well pumpage; and evapotranspiration.



FigureI. 6.11. Schematic diagram of a typical aquifer test showing the various measurements
(Heath, 1983)

6.6.1 Recharge from precipitation

Precipitation that percolates through the soil ultimately can recharge the groundwater system. This typically occurs in areas of relatively high topographic level and is controlled by the permeability of the soils. Individual recharge events can be identified as rises in water table hydrographs. If the porosity of the aquifer material is known, generally ranging from 5 to 40 per cent, an estimate of the recharge volume can be made for a unit area of aquifer, as water-level rise x porosity (as a fraction) x area.

6.6.2 Groundwater–surface water relationships

In many areas, the groundwater system is directly linked to the surface water system in such a way that even a large volume of water can flow from one to the other. It is important to understand this relationship.

6.6.2.1 Gaining and losing streams

The elevation of water levels in a stream relative to the adjacent water level in a surficial or water table aquifer will control the direction of flow between these two parts of the hydrological system. The situation where the stream level is below the water table in the underlying aquifer that drives flow upward to the stream is referred to as a gaining stream (Figure I.6.12, top). The reverse situation where the stream level is above the water table in the underlying aquifer that drives flow downward to the aquifer is referred to as a losing stream Figure I.6.12, middle). In some cases, especially in an arid setting, the aquifer may not have a saturated connection with the stream. This case is also a losing stream (Figure I.6.12, bottom).

The groundwater recharge from a losing stream or groundwater discharge to a gaining stream can be quantified or measured in several ways:

(a) For a gaining stream, examination of a long-term hydrograph record can indicate the base flow. The base-flow portion of a stream hydrograph (Volume II, 6.3.2.2.2) is likely to include the groundwater discharge. Other constant discharges from reservoirs or sewage treatment plants, for example, can also contribute to base flow;

(b) For either a losing or gaining stream, differential streamflow discharge measurements taken at an upstream and a downstream point on a reach will show the loss or gain within the uncertainty associated with the measurement (Chapter 5). The selected stream reach should not have any other inputs or outputs, such as tributaries, sewage treatment plants, water intake plants or irrigation returns;

(c) A direct measurement of the discharge to or from a stream can be made with seepage meters. These are instruments that are placed in the stream bed and that retain the volume of water seeping through the stream bed for subsequent measurement (Carr and Winter, 1980). Some of these devices may only be able to work in a gaining stream condition. These instruments are sensitive to, and may not be able to work

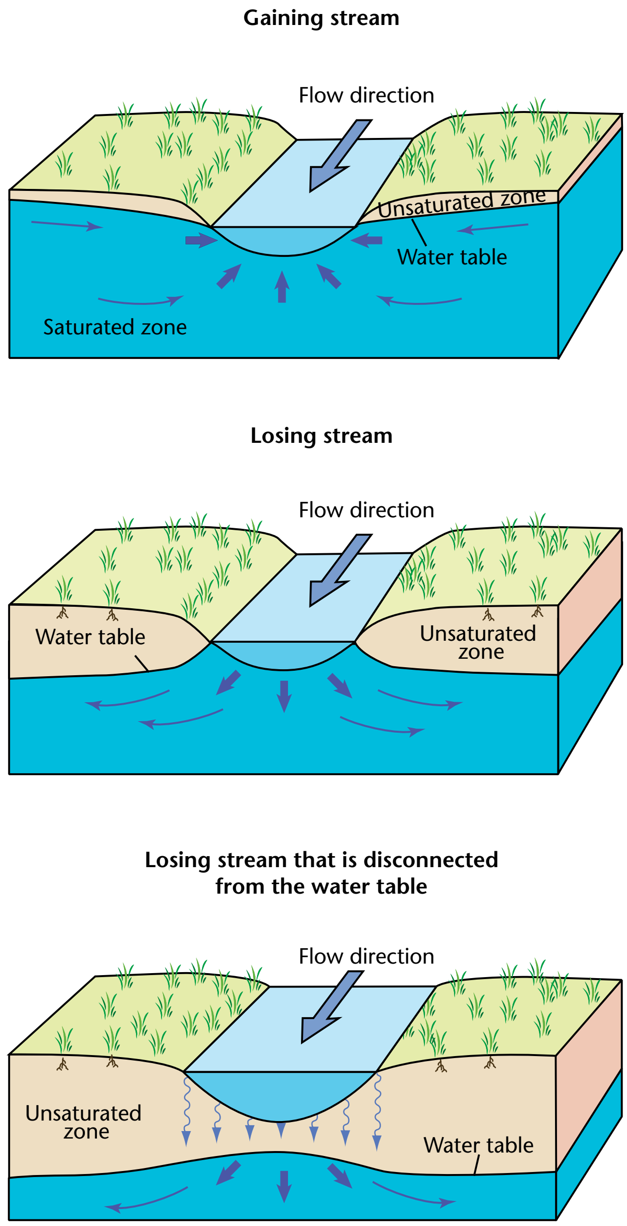


Figure I.6.12. Relative configuration of groundwater level and stream level for gaining and losing streams (Winter and others, 1998) in, relatively high stream velocities because of scour.

6.6.2.2 Springs and seeps

Discharge from springs and seeps, which represent localized groundwater discharge, can be measured using standard stream discharge measurement procedures (Chapter 5).

6.6.2.3 Effects of evapotranspiration on groundwater system

Deep-rooted plants and plants in general in areas of a shallow water table can derive water from the groundwater system. The standard methods to determine potential evapotranspiration rates can be implemented for areas where groundwater is likely to be involved (Chapter 4).

6.6.3 Well pumpage

Pumpage from individual wells and the cumulative effects of pumpage of many wells in an area can have a very significant impact on groundwater levels and the groundwater system in general. It is a common occurrence for the drawdown from a pumped well to cause a nearby stream to change from a gaining to a losing configuration, underscoring the importance of tracking the location and effect of well pumpage. In particular, wells for public supply, industrial or commercial use, and for irrigation pump the largest amounts. A quantification of the pumpage amounts requires a tallying of reports by the well owners, or lacking those reports, an effort to measure the significant users. The procedures detailed in 6.4 can be used to make those measurements. As pumping can change with the demands of the well users, keeping track of those changes can require much effort. It is possible to develop a relation between the pump discharge and the pump's electrical or fuel usage. If such data are available, this can ease the burden of compiling or collecting pumpage data for a large number of wells.

6.7 USE OF DATA IN GROUNDWATER MODELS

A primary role of a model is the integration of hydrogeological framework information, water-level data, pumpage, and recharge and discharge information in order to understand the relative importance of the various processes of the groundwater system, and to appraise the capacity or capability of the groundwater system to meet general or specific (usually water supply) goals. The commonly used modelling options range from development of a simple water budget to the development of a complex digital groundwater-flow model. It is beyond the scope of this Guide to provide the detailed background for the development, calibration and use of groundwater models; however the methods and approaches for the collection of data outlined in this chapter and in Table I.6.3 provide the necessary foundation to the development of models. Further discussion on the subject of groundwater modelling as well as references on the subject are provided in Volume II, 6.3.5.2.

Table I.6.3. Data requirements for groundwater models

Hydrogeological framework	Extent and thickness for each aquifer
	Extent and thickness for each confining bed
Hydrological boundaries and stresses	Amount and location of recharge (net precipitation, leakage from streams)
	Amount and location of discharge (well pumpage, leakage to streams, spring flow, evapotranspiration)
Distribution of hydraulic parameters	Aquifer hydraulic conductivity or transmissivity
	Aquifer storage coefficient
	Confining bed properties
Calibration data	Groundwater levels, with concurrent stream base flow, well pumpage, recharge, etc.

6.8 REMOTE-SENSING [HOMS D]

Currently, there are no direct remote-sensing techniques to map areas of groundwater. However, indirect information can be obtained from remote-sensing sources.

Remote-sensing techniques used to map areas of groundwater include aerial and satellite imagery in the visible, infra-red and microwave regions of EMS. In particular, satellite imagery enables a view of very large areas and achieves a perspective not possible from ground surveys or even low-level aerial photography. Although remote-sensing is only one element of any hydrogeological study, it is a very cost-effective approach in prospecting and in preliminary surveys. Owing to the intervening unsaturated zone of soil, most remote-sensing data cannot be used directly, but require substantial interpretation. As a result, inference of location of aquifers is made from surface features. Important surface features include topography, morphology and vegetation. Groundwater information can be inferred from landforms, drainage patterns, vegetation characteristics, land-use patterns, linear and curvilinear features, and image tones and textures. Structural features such as faults, fracture traces and other linear features can indicate the possible presence of groundwater. Furthermore, other features, such as sedimentary strata or certain rock outcrops, may indicate potential aquifers. Shallow groundwater can be inferred by soil moisture measurements, changes in vegetation types and patterns, and changes in temperature. Groundwater recharge and discharge areas within drainage basins can be inferred from soils, vegetation and shallow or perched groundwater (Engman and Gurney, 1991).

Airborne exploration for groundwater has recently been conducted using electromagnetic prospecting sensors developed for the mineral industry (Engman and Gurney, 1991). This type of equipment has been used to map aquifers at depths greater than 200 m (Paterson and Bosschart, 1987).

Aerial photography supplemented by satellite data from Landsat or SPOT are widely used for groundwater inventories, primarily for locating potential sources of groundwater. This technique permits inferences to be made about rock types, structure and stratigraphy. IR images are valuable for mapping soil type and vegetative surface features used in groundwater exploration. Springs can best be detected using IR and thermal imagery. Underwater springs can be detected by this method (Guglielminetti and others, 1982). Furthermore, through temperature differences, thermal IR imagery has the potential to deduce information on subsurface moisture and perched water tables at shallow depths (Heilman and Moore, 1981*a* and 1981*b*; Salomonson, 1983; van de Griend and others, 1985).

Passive microwave radiometry can be used to measure shallow groundwater tables. A dual frequency radiometer has been used on an aircraft to measure water table depths of 2 m in humid areas and 4 m in arid areas (Shutko, 1982; 1985; 1987).

Radar has an all-weather capability and can be used to detect subtle geomorphic features even over forested terrain (Parry and Piper, 1981). Radar is also capable of penetrating dry sand sheets to disclose abandoned drainage channels (McCauley and others; 1982; 1986), and can also provide information on soil moisture (Harris and others, 1984). Radar images may be used to detect water which is several decimetres below the ground surface in arid areas, owing to the increase in soil moisture near the surface. Near-viewing short pulse radars installed on mobile ground or aircraft platforms provide information on the depth to a shallow water table down to 5–50 m (Finkelstein and others, 1987). Radar imagery has the potential to penetrate the dense tropical rainforest and rainfall, and yield information that can be used to produce a geological map for use in groundwater exploration (Engman and Gurney, 1991). Radar imagery has been used successfully to reveal previously unchartered network of valleys and smaller channels buried by the desert sands (McCauley and others, 1986).

A comprehensive state-of-the-art review of remote-sensing applications to groundwater (Meijerink in Schultz and Engman, 2000) as well as references to a number of specific applications are included in the list of references and further reading below.

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CHAPTER 7

WATER QUALITY AND AQUATIC ECOSYSTEMS

7.1 GENERAL

This chapter discusses general aspects of water quality sampling and specific aspects related to the sampling of rivers, streams, lakes, reservoirs and groundwaters. More detailed discussions can be found in the references (WMO, 1988; UNEP/WHO/UNESCO/WMO, 1992) and in more specialized publications related to biological water quality (American Public Health Association and American Water Works Association, 1999; Genin and others, 1997). Guidance on chemical or isotopic sampling and analytical techniques are provided in a long list of references by the International Atomic Energy Agency (IAEA).

7.2 SPECIFIC REQUIREMENTS FOR WATER-QUALITY MONITORING

There are several approaches to water quality monitoring. Monitoring can be accomplished through a network of strategically located long-term stations, by repeated short-term surveys, or by the most common approach, a combination of the two.

The location of stations and samplings should take into account the following factors:

(a) Accessibility and travel time to the laboratory (for deteriorating samples);
(b) Available staff, funding, field and laboratory data handling facilities;
(c) Inter-jurisdictional considerations;
(d) Population trends;
(e) Climate, geography and geology;
(f) Potential growth centres (industrial and municipal);
(g) Safety of personnel.

Sampling frequency depends on the objectives of the network, the importance given to the sampling station, the levels of the measured values, the spacial variability of the studied parameters and, most importantly, on the available funding. Without sufficient previous information, an arbitrary frequency is chosen based on knowledge of the local conditions. This frequency may be adjusted after a sufficient number of samples have been taken and analysed and note has been taken of the substances present, their concentrations and the observed variability.

The choice of sampling stations also depends on the present and planned water use, the stream or lake water quality objectives or standards, the accessibility of potential sampling sites (landowners, routes, airstrips), the existence of services such as electricity, and already existing water quality data. Figure I.7.1 shows the steps to follow for the choice of sampling sites.

7.2.1 Water-quality parameters

The parameters that characterize water quality may be classified in several ways, including:

(a) Physical properties, for example, temperature, electrical conductivity, colour and turbidity;
(b) Elements of water composition, such as pH, alkalinity, hardness, Eh or the partial pressure of carbon dioxide;
(c) Inorganic chemical components, for example, dissolved oxygen, carbonate, bicarbonate, chloride, fluoride, sulfate, nitrate, ammonium, calcium, magnesium, sodium potassium, phosphate and heavy metals;
(d) Organic chemicals, for example, phenols, chlorinated hydrocarbons, polycyclic aromatic hydrocarbons and pesticides;
(e) Biological components, both microbiological, such as faecal coliforms, and macrobiotic, such as worms, plankton and fish, or vegetation.

7.2.2 Surface-water quality

The programme objectives will often precisely define the best locations for sampling in a river or lake system. For example, in order to determine the effect of an effluent discharge on a receiving stream, sampling locations upstream and downstream of the discharge would be required. In other cases, both location and frequency of sampling will be determined by anti-pollution laws or by a requirement for a specific use of a water body. For example, a permit to discharge surface waters may outline details of monitoring, such as location, number of samples, frequency and parameters to be analysed.

Sampling strategies are quite different for different kinds of water bodies and media, for example, water, sediment or biota. If the objective concerns the impact of human activities on water quality in a given river basin, the basin can be separated into natural and altered regions. The latter can be further subdivided into agricultural, residential and industrial zones. In acid-deposition studies, an important factor is the terrain sensitivity to the deposition. Figures I.7.2 and I.7.3 give some examples as to how sampling stations could be located to meet specific objectives on river and lake systems.

Collecting relevant information on the region to be monitored is an essential step in water quality assessment. This information includes the geological, hydrological and climatic aspects. In addition, demographic conditions and planned water use (water intakes, waste outlets, main drainage, irrigation schedules and flow regulation) are also relevant.

For surface waters, the distance downstream to the point of complete mixing is roughly proportional to the stream velocity and to the square of the width of the channel. For shallow rivers, waters attain homogeneity vertically below a source of pollution. Lateral mixing is usually attained much more slowly. Thus, wide swift-flowing rivers may not be completely mixed for many kilometres downstream from a pollution point source. Lakes can be vertically stratified owing to temperature or high-density saltwater intake.

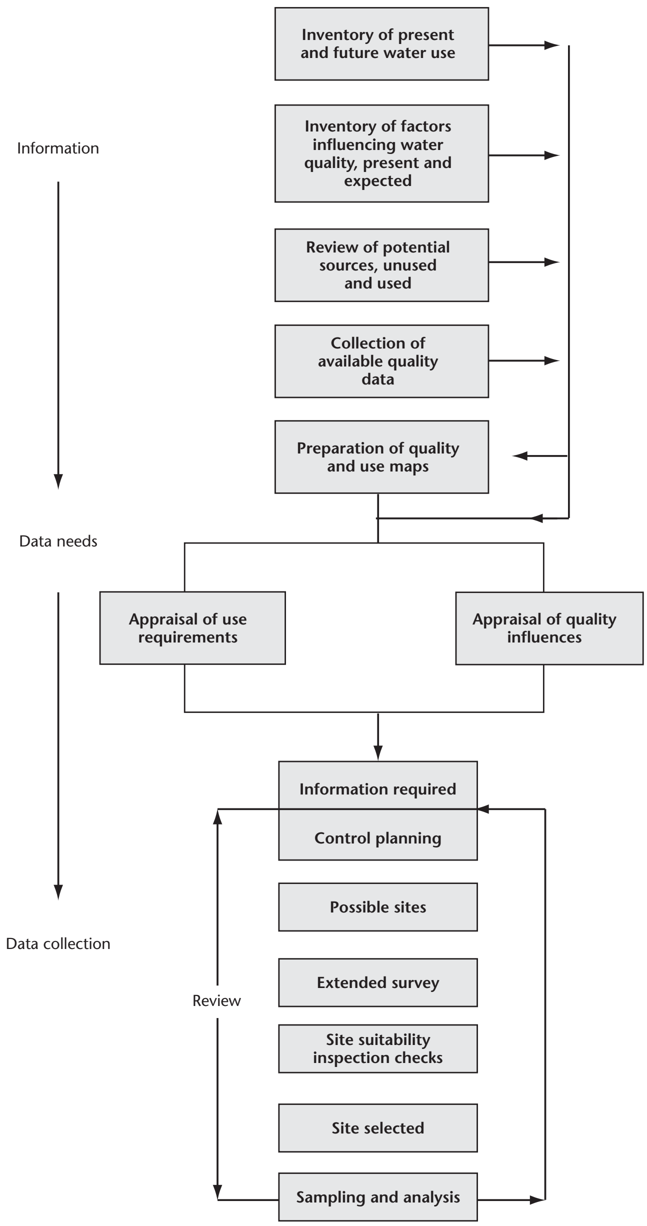
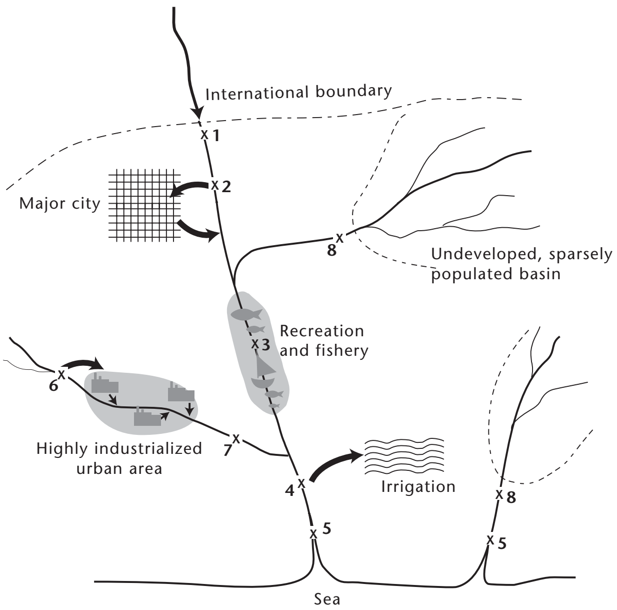
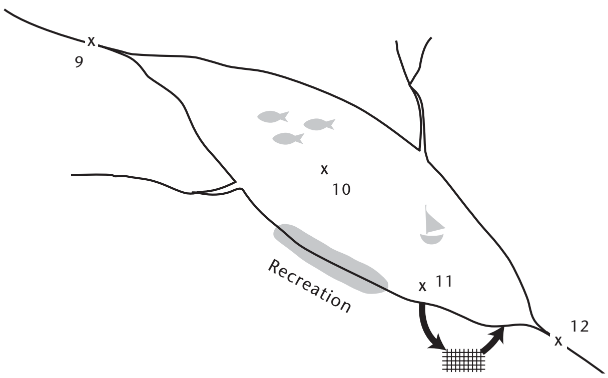


Figure I.7.1. Scheme for the selection of water quality sampling sites



Station	*Criteria*
1	Immediately downstream of an international boundary
2	Diversion for public supply of large town
3	Important fishing, recreation and amenity zone
4	Diversion for large-scale agricultural irrigation
5	Freshwater tidal limit of major river
6	Diversion for large industrial supply
7	Downstream of industrial effluent discharges and important tributary influencing main river
8	Baseline station, water in natural state

Figure I.7.2. Monitoring site: rivers



Station	*Criteria*
9	Principal feeder tributary
10	General water quality of lake
11	Water supply for major city
12	Water leaving lake

Figure I.7.3. Monitoring site: lakes

Various protocols are recommended to determine representative sampling in the cross-section of the river. For example, six samples analysed in duplicate, taken from three positions across the river and at two depths or mid-depth samples at the quarter points, or other equal distance points across the width of the river. If a representative sample cannot be obtained, it is advisable to select another site, either immediately upstream or downstream. The other alternative is to obtain a flow-weighted composite sample from samples collected at verticals on the cross-section.

Longitudinal mixing of irregular or cyclic discharges into a river will have a secondary influence on the location of a sampling site. Their effects need to be taken into account in deciding the frequency of sampling and in interpreting the data.

For lake stations, the recommended practice is to sample for five consecutive days during the warmest part of the year and for five consecutive days every quarter. Alternatively, they should be sampled at least six times a year, together with the occasional random sample, to cover the periods such as open water prior to summer stratification, during mixing following summer stratification, under ice, and during the periods of snow melt and runoff.

Similarly, additional samples of rivers should be taken, if possible, after storm events and during snow melt and runoff. When parameters are plotted against time, some cyclic variation may be apparent amidst the random fluctuations.

The detection of cyclic events requires a sampling interval that is no longer than one third of the shortest cycle time and a sampling period at least ten times as long as the longest cycle. Therefore, long-period cycles will not be verified in the initial surveys, but become apparent during the operation of the network. In order to detect the cyclic variations, some random sampling is desirable, for example, on different days of the week or at different times of the day.

7.2.3 Precipitation quality

Specific aspects concerning the quality of precipitation, particularly sampling equipment, are discussed in 3.16. In general, sampling sites should be selected to give accurate and representative information concerning the temporal and spatial variation of chemical constituents of interest. Important factors to take into consideration are prevalent wind trajectories, sources for compounds of interest, frequency of precipitation events (rain, snow or hail), and

other meteorological processes that influence the deposition. The following criteria should be considered:
(a) No moving sources of pollution, such as routine air, ground or water traffic, should be within 1 km of the site;
(b) No surface storage of agricultural products, fuels or other foreign materials should be within 1 km of the site;
(c) Samplers should be installed over flat undisturbed land, preferably grass-covered, surrounded by trees at distances greater than 5 m from the sampler. There should be no wind-activated sources of pollution nearby, such as cultivated fields or unpaved roads. Zones of strong vertical eddy currents, eddy zones leeward of a ridge, tops of wind-swept ridges and roofs of buildings, particularly, should be avoided because of strong turbulence;
(d) No object taller than the sampler should be within 5 m of the site;
(e) No object should be closer to the sampler than a distance of 2.5 times the height by which the object extends above the sampler. Particular attention must be given to overhead wires;
(f) The collector intake should be located at least 1 m above the height of existing ground cover to minimize coarse materials or splashes from being blown into it;
(g) Automatic samplers require power to operate lids and sensors and, in some cases, for refrigeration in the summer and thawing in the winter. If power lines are used, they must not be overhead. If generators are used, the exhaust must be located well away and downwind from the collector;
(h) To address issues on a continental scale, sites should preferably be rural and remote, with no continuous sources of pollution within 50 km in the direction of the prevalent wind direction and 30 km in all other directions.

It may not be possible to meet all of these criteria in all cases. The station description should refer to these criteria and indicate the exact characteristics of each location chosen as a sampling site.

In the case of large lakes, the precipitation over the lake may not be as heavy as along the shores and the proportion of large particles may be smaller. In order to sample in the middle of a lake, the sampler can be mounted on a buoy, rock, shoal or small island.

Precipitation sampling can be taken for each rain event or over a monthly period. In this case, rain is preserved for the same period before being analysed. The analysis of event-precipitation samples enables pollutants associated with a particular storm to be determined, and a wind-trajectory analysis can determine probable sources. However, this sampling regime is very sensitive. The same statistical considerations concerning frequency of sampling apply here as for surface-water sampling.

7.2.4 Groundwater quality

The quality of groundwater is subject to change and deterioration as a result of human activity. Localized point sources of pollution include cesspools and septic tanks, leaks in municipal sewers and waste ponds, leaching from garbage dumps and sanitary landfills, seepage from animal feedlots, industrial waste discharges, cooling water returned to recharge wells, and leaks from oil tankers or pipelines. Larger geographical areas may suffer degradation of groundwater quality because of irrigation water returns, recharge into aquifers of treated sewage or industrial effluents, and intrusion of seawater in coastal zones or from other highly saline aquifers.

Water samples can be collected from free-flowing artesian wells or pumped wells. The wells should be pumped long enough to ensure that the sample is representative of the aquifer and not of the well. This is particularly necessary for open wells or where a well has a lining subject to corrosion. Portable pumps are needed in case of non-equipped wells. For sampling at different depths, mechanical or pneumatic equipment should be used to isolate specific sites. Sampling in shallow aquifers and saturated zones between impermeable layers can often be obtained by lowering a piezometer to the desired depth. The basic parameters used to define surface water quality can also be used for groundwater monitoring with the exception of turbidity, which is not usually a problem.

A good deal of hydrogeological information may be necessary to plan a groundwater sampling programme. Data on water levels, hydraulic gradients, velocity and direction of water movements should be available. The velocity of groundwater movement within the aquifers is highly variable. It can vary from 1 m y^{-1} in flat regions with low recharge to more than 1 m s^{-1} in karst aquifers. An inventory of wells, boreholes and springs fed by the aquifer should be drawn up and details of land use should be recorded.

For the collection of water samples (and water levels), an existing well is a low-cost choice, although they are not always at the best location or made of non-contaminating materials. A well that is still in use and pumped occasionally is preferable to one that has been abandoned. Abandoned or unused wells are often in poor condition with damaged or leaky casings and corroded pumping equipment. It is often difficult to measure their water levels and there may be safety hazards.

Changes in groundwater can be very slow and are often adequately described by monthly, seasonal or even annual sampling schedules. In some cases, such as alluvial aquifers with large inputs from surface drainage, the temporal variation of water quality can be very relevant.

7.2.5 **Sediment quality**

Most of the selection criteria outlined in previous sections also apply to sampling for sediments (5.5.3 and 5.5.4). Therefore, only additional special recommendations will be described here.

For rivers where sediment-transport data are required, it is necessary to locate the sampling sites near a gauging station so that accurate stream-discharge information is available at all times. Sampling locations immediately upstream from confluences should be avoided because they may be subject to backwater effects. In streams too deep to wade, sampling sites should be located near bridges or cableways. When sampling from bridges, the upstream side is normally preferred. Sampling in areas of high turbulence, such as near piers, is often unrepresentative. Attention should also be paid to the accumulation of debris or trash on the piers, as this can seriously distort the flow and hence the sediment distribution. An integrated sample obtained by mixing water from several points in the water column according to their average sediment load can be considered as a representative sample as long as there is good lateral mixing.

The best places to sample bottom deposits in fast-flowing rivers are in shoals, at channel bends and at mid-channel bars or other sheltered areas where the water velocity is at its minimum.

Sampling sites should be accessible during floods, since sediment-transport rates are high during these times.

For identification of peak pollution loads in rivers, two cases must be considered:

(a) For pollution from point sources, sampling should be done during low-flow periods, when pollution inputs are less diluted;
(b) When pollutants originate from diffuse sources, such as runoff of agricultural nutrients or pesticides, sampling must be focused on flood periods during which the pollutants are washed out of the soil.

If one of the objectives is to quantify the transport of sediment in the river system, it should be noted that peak concentrations of sediment do not necessarily correspond with times of peak flow. Also, a series of high flow rates will lead to progressively lower sediment peaks – an exhaustion effect arising from the depletion of material available for re-suspension. For lakes, the basic sampling site should be located at the geographic centre of the lake. If the lake is very large (area > 500 km^2), several base stations may be needed. If various sediment types are to be sampled, then data from acoustic surveys (echo-sounders) can be used both to identify the type of surficial material (sand, gravel or mud) and to indicate the presence of layering below the surface.

Secondary sampling sites should be located between the base station and major tributary inlets or pollutant sources. A common strategy is to place points down the long axis of the lake with occasional cross lines. Three to five stations should usually give a good approximation to the sediment quality of an average size lake. For statistical validity, however, a larger number of sampling sites will probably be required.

Sampling frequency in lakes is influenced by the concentrations of suspended sediment which is generally low. Sediment traps should be operated during the periods of maximum and minimum algal productivity and at times of high input of sediment from rivers. Repeat sampling of bottom sediments in lakes needs to take into account the rates of sediment accumulation. Basins in cool, temperate climates often have accumulation rates in the order of 0.1–0.2 mm y^{-1}. A re-sampling period of five years would then be too soon to provide worthwhile new information, unless the presence of a new pollutant were to be tested.

7.3 **SAMPLING METHODS** [HOMS E05]

Sampling is the process of collecting a representative quantity of water from a river, lake or well. Sampling methods are determined by a number of factors, including the type of material being sampled, the type of sample and the quality parameter being analysed, which in turn determine the equipment and procedures to be used.

Sampling procedures should be adapted to different components such as the following:
(a) Steady: the components do not change with time;
(b) Nearly steady: the components change with time but can be stabilized during a period of 24 hours or less after appropriate treatment;
(c) Unsteady: the components change rapidly and cannot be stabilized.

Groups (a) and (b) include components that are laboratory tested, whereas those included in group (c) must be measured in situ.

7.3.1 Types of water samples

7.3.1.1 Grab samples

Grab samples are appropriate when it is desired to characterize water quality in a particular location. They are also used to establish the water quality history based on relatively short time intervals. A discrete grab (or spot) sample is taken at a selected location and depth. A depth-integrated grab sample is collected over the depth of the water column at a selected location and time.

7.3.1.2 Composite samples

A composite sample is obtained by mixing several samples to obtain an average value of water quality over the sampling period. Discrete or continuous sampling can be used and the mixing proportion is calculated on a time or discharge basis. A portion of the composite sample is then analysed. An obvious advantage is in the economy of reducing the number of samples to be analysed. However, composite samples cannot detect changes in parameters occurring during the sampling period.

There are two main types of composite samples: sequential and flow-proportional.

A sequential composite is constituted by continuous, constant sample pumping, or by mixing equal water volumes collected at regular time intervals.

A flow-proportional composite is obtained by continuous pumping at a rate proportional to the flow, mixing equal volumes of water collected at time intervals that are inversely proportional to the rate of flow, or by mixing volumes of water proportional to the flow collected at regular time intervals.

7.3.2 Collecting a representative water sample

For sampling at sites located on a uniform, well- mixed reach of stream, the collection of depth-integrated samples in a single vertical may be adequate. For small streams, a grab sample taken at the centroid of flow is usually adequate.

In other cases the number of samples taken will depend on the width, depth, discharge, amount of suspended sediment being transported and aquatic life present.

Three to five verticals are usually sufficient; fewer are necessary for narrow or shallow streams.

One common method is the equal-width-increment method, in which verticals are spaced at equal intervals across the stream. The equal-discharge-increment method requires detailed knowledge of the streamflow distribution in the cross-section to subdivide the cross-section into verticals spaced in proportion to the incremental discharges.

7.3.3 Sampling for the analysis of water stable isotopes

To complete the study of water quality, it is interesting to consider the stable isotopes of a water molecule (oxygen-18 and deuterium). For instance, in coastal areas, the analysis of water stable isotopes – both in surface and groundwater – is useful to detect whether the salinity of inland waters is due to anthropic pollution, agriculture activities or upstream saline water. Isotopes also permit the localization of aquifers, the study of surface and groundwater linkage or the detection of natural processes affecting waters such as mixing or evaporation. Detailed information on the use of stable isotopes relevant to this subject is provided in the references (Mook, 2000).

Isotopic analyses require specialized laboratories, but the required water samplings procedures are quite simple. Sampling procedures that take account of the specific protocol for isotope sampling and conditioning are as follows:
(a) Use painted glass bottles or high-density plastic (10 to 60 ml), generally 50-ml containers and hermetic sealing caps (reinforced by an interior plastic plug);
(b) Rinse the containers three times with the water to be sampled;
(c) Fill the bottle to the brim; this avoids evaporation, which could enrich the residual water and vapour pressure. If transported by air, bottles

should not be filled and the cap should be insulated with a paraffin film;
(d) Snow samples should be collected in clean plastic bags (using non-contaminating gloves), then gradually melted before being put into containers;
(e) Ice samples are preserved in the frozen state to reach the laboratory;
(f) Samples should not be filtered except when they have been in contact with oil (used for protection against the evaporation of collected precipitation);
(g) Sample may be preserved for a long time (more than a year) in a cool, dark environment.

7.3.4 Radioactivity measurement

Detailed instructions for the analysis of radioisotopes associated with water quality together with recommended containers and preservation methods are provided in the references (United States Geological Survey, 1984; IAEA, 2004) and further reading at the end of this chapter

7.3.4.1 Sources of radioactivity in water

Sources of radioactivity in water may be natural or due to human activities. The main natural sources are derived from the weathering of rocks containing radioactive minerals and the fallout of cosmic-ray nuclides. The major sources of radioactivity due to human activities are: uranium mining, nuclear-power industries, nuclear weapons testing, and the peaceful applications of nuclear materials and devices, for example, energy production.

The principal radionuclides introduced naturally into surface water and groundwater are uranium, radium-226, radium-228, radon, potassium-40, tritium and carbon-14. All but the last two derive from radioactive minerals. In areas where radioactive minerals are abundant, natural uranium is the major radioactive constituent present in water. Tritium and carbon-14 are produced by the interaction of cosmic-ray neutrons with nitrogen in the upper atmosphere. The tritium (^3H) isotope, a constituent present in water, is eventually rained out as precipitation. Radioactive carbon is incorporated into atmospheric carbon dioxide.

Both tritium and radioactive carbon are also produced by thermonuclear power testing and are currently used for groundwater dating (time elapsed between aquifer recharge and water sampling). Since 1970 the nuclear power industry has probably been the larger source of tritium. Strontium-90 and Cesium-137 are the major man-made radioisotopes of concern in water.

The geochemical behaviour of a daughter element may be grossly different from that of the radioactive parent element, although its occurrence, distribution and transport may be governed by those of the parent. The International Commission on Radiological Protection recommends the maximum permissible concentration values in water.

7.3.4.2 Collection and preservation of samples for radioactivity measurement

Acceptable containers (generally four-litre bottles) are made of polypropylene, polyethylene or Teflon. They should be pretreated in laboratory by filling them with concentrated nitric acid for a day, rinsing with detergent, and then rinsing several times with highly purified water.

For tritium, samples should be collected in high-density plastic bottles holding between 0.5 and 1.0 l.

For carbon-14, according to specialized laboratory requirements, one procedure is to take one litre of water in high precision bottles or to dissolve about 2.5 g of precipitate into more than 100 l of water in case of low carbon content.

The principal problem encountered in preserving these samples is adsorption on the walls of the container or on suspended matter. To analyse the total radio-element quantities and to minimize adsorption, 2 ml of concentrated HCl per litre of sample, or nitric acid to one per cent concentration, are added.

Generally, to minimize analysis cost, it is advisable to analyse an annual composite sample by mixing aliquots from each monthly sample.

If a significant level of radioactivity over environmental levels is found, the samples making up the composite are analysed individually to locate the sample(s) that has (have) the higher than expected radioactivity level.

7.3.5 Field sampling equipment and techniques

7.3.5.1 Grab samplers

Grab samplers may be classified as those appropriate only for volatile constituents, such as for dissolved gases and others for non-volatile constituents. Both discrete (surface or specific depth) and depth-integrating types of samplers are available. Both may be used to collect water for the determination of non-volatile constituents.

To obtain an approximate depth-integrated sample, an open sampling apparatus should be lowered to the bottom of the water body and raised to the surface at a constant rate so that the bottle is just filled on reaching the surface. A sampling iron can be used for this purpose: it is a device, sometimes made of iron, used to hold sample bottles. The sample bottles are placed in the sample iron and are secured by the neck holder. In some cases, sampling irons may have provision for additional weights to ensure a vertical drop in strong currents.

Depth integration may not be possible in shallow streams where the depth is insufficient to permit integration. In such cases, care must also be taken not to disturb the river bottom when taking a sample. One suggestion in such cases is to dig a hole in the bottom, let the stream settle, and sample down to the top of the hole.

Discrete samplers are used to collect water samples at a specific depth. An appropriate sampler is lowered to the desired depth, activated and then retrieved. Van Dorn, Kemmerer and pump samplers are frequently used for this purpose:

(a) Van Dorn bottle – The Van Dorn bottle (Figure I.7.4) is designed for sampling at a depth of 2 m. Its horizontal configuration should be used when samples are taken at the bottom, at the sediment-water interface;
(b) Kemmerer sampler – It is one of the oldest types of messenger-operated vertical samplers. It is commonly used in water bodies with a depth of 1 m or greater. The Kemmerer sampler (Figure I.7.5) is available in volumes ranging from 0.5 to 8 l;
(c) Pumps – Three types of pumps – diaphragm, peristaltic and rotary – are available to collect samples from specified depths. In general, diaphragm pumps are hand operated. The peristaltic and rotary pumps require a power source and consequently have limited field utility. Peristaltic pumps are not recommended for the collection of samples for chlorophyll analysis because damage to the algal cells may occur. All pumps must have an internal construction that does not contaminate the water sample. Input and output hoses must also be free of contaminants.

The Van Dorn samplers have an advantage over the Kemmerer bottle in that their lids do not lie in the path of the flow of water through the sampler, which can cause eddies and disturbance.

A multiple sampler (Figure I.7.6) permits the simultaneous collection of several samples of equal or different volumes at a site. Each sample is collected in an individual bottle. When the samples are of equal volume, information concerning the instantaneous variability between the replicate samples can be obtained. The sampler may be altered to accommodate different sizes and numbers of bottles according to the requirements of specific programmes. This may be done by changing cup

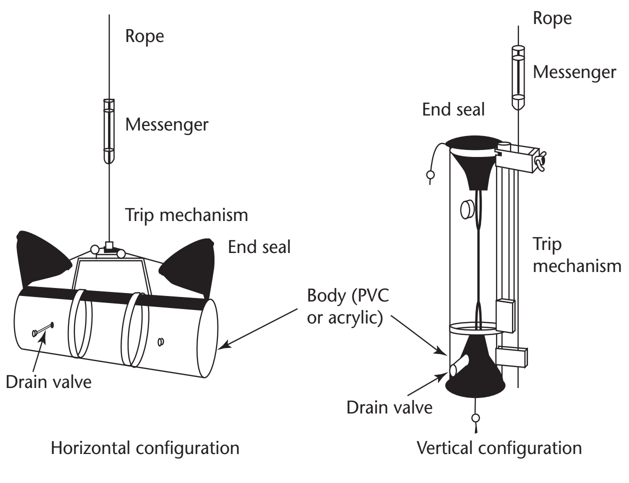


Figure I.7.4. Van Dorn bottle

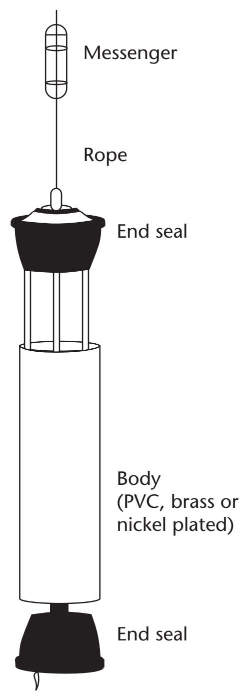


Figure I.7.5. Kemmerer sampler

sizes, length of cup sleeves and the configuration and size of openings in the clear acrylic top.

7.3.5.2 Dissolved-oxygen sampler

A typical sampler for dissolved-oxygen concentration and Biochemical Oxygen Demand (BOD) is illustrated in Figure I.7.7. This sampler must be pulled up open, thus some mixture with the upper water layers is possible. If certain grab samplers are fitted with bottom drain tubes, they may be used by running the sample into the bottom of the analysis container. The samples should be collected in narrow-mouthed BOD bottles that have bevelled glass stoppers to avoid entrapment of air in the samples. Sampling of shallow streams is not advisable with this sampler. In this case, sample agitation (bubbling) should be minimized by gently tilting a BOD bottle downstream.

7.3.5.3 Automatic samplers

Automatic samplers range from elaborate instruments with flexible sampling programmes, which require external power and permanent housing, to simple, portable, self-contained devices, such as a submerged bottle with a rate of filling determined by a slow air bleed. These devices are often programmed to sample over a 24-hour period.

They reduce costly personnel requirements if frequent sampling is required. If the site has automatic flow-measurement capability, some automatic samplers can provide flow-proportional samples. Both composite- and individual-sample models are available.

7.3.5.4 Sampling procedures as influenced by station, location and season

In the field, the sampling situation determines which of several different sampling techniques is required. Some of the practical sampling considerations related to location and season of sampling are outlined below. Detailed procedures for sampling are given in the *Manual on Water Quality Monitoring: Planning and Implementation of Sampling and Field Testing* (WMO-No. 680).

Sampling from bridges is often preferred because of the ease of access and safety under most conditions of flow and weather. However, vehicular traffic is a potential hazard and should be considered.

Boats provide more flexibility and reduce the time of travel between sampling points. The sampling point must be identified by triangulation from landmarks, and here also the hazards of navigation, high flows and storms have to be considered (8.5). Aircraft, including helicopters, are expensive, but fast and flexible. Tests have shown that the disturbance of water under helicopters does not significantly affect even dissolved-oxygen water samples. Bank-side sampling should only be used when no alternative is possible. The sample should be taken in turbulent water or where the water is fast and deep. A sampling iron is often used when water samples are collected from shores, stream banks and wharves.

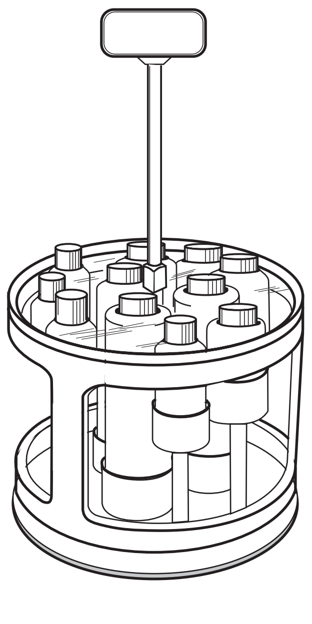


Figure I.7.6. Multiple sampler

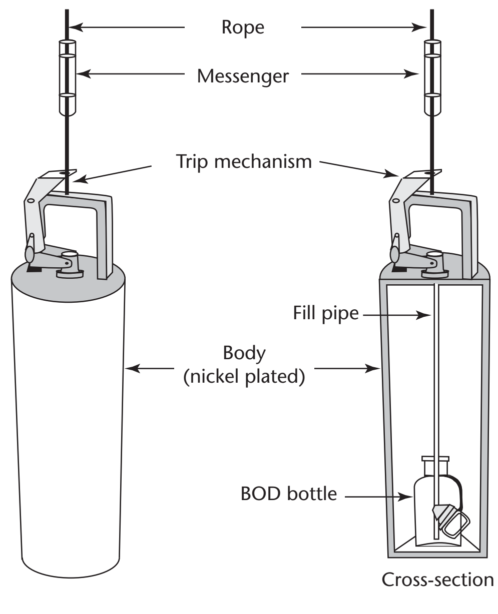


Figure I.7.7. Dissolved oxygen sampler

Sampling of ice and snow under winter conditions requires somewhat different techniques. The safety precautions outlined in 8.9 should be followed. Overlying snow should be removed from the ice surface to provide a suitable working area.

7.4 PREPARATION FOR FIELD TRIPS

7.4.1 General preparation

(a) Obtain specific instructions on sampling procedures;
(b) Prepare an itinerary according to the sampling schedule (also 2.4.3);
(c) Prepare lists of required equipment and materials;
(d) Ensure that all sample bottles have been cleaned in accordance with standard procedures;
(e) Ensure that the laboratory has prepared the chemical reagents and standards needed for the trip;
(f) Prepare a checklist (7.4.3 below).

7.4.2 Selection of sample volumes

The volumes of the particular samples required depend on the type and number of parameters to be analysed, the analytical method and the expected concentrations of the constituents in the water. Laboratory personnel will specify the sample volume required. The required sample volume can be determined by listing all of the parameters that are preserved in the same way, totalling the volume needed for preparation and analysis, and then multiplying by two for duplicate and three for triplicate analyses. The following points should be kept in mind:
(a) When contact with air is to be avoided, the sample container should be completely filled;
(b) When samples require vigorous shaking before taking aliquots for analysis, the container should not be completely filled;
(c) Where both requirements must be met, the bottle should be completely filled, but pieces of clean, sterile inert solid such as beads should be added;
(d) When the sample contains discrete particles, for example, undissolved materials, bacteria and algae, a volume of sample larger than usual may be needed to minimize errors.

7.4.3 Checklist prior to field trip

(a) Check and calibrate meters (pH, specific conductance, dissolved oxygen and turbidity) and thermometers;
(b) Replenish supplies of reagents for dissolved-oxygen determinations as well as reagents for chemical preservation;
(c) Obtain fresh buffer solutions. The pH values for the buffers should be close to the values expected in the field;
(d) Obtain KCl solution for pH probes;
(e) Obtain road maps, station-location descriptions, field sampling sheets, sampling bottles, labels, samplers, preservation reagents, pipettes and equipment manuals;
(f) Obtain writing materials, extra rope and a comprehensive toolbox;
(g) Obtain electrical cables if the equipment has in-field charging capabilities;
(h) Obtain ultrapure water (resistivity of 18.2 MΩ) and prepare clean beakers for pH, blanks and buffer measurements;
(i) If field filtering is required, obtain filtering gauge and perfectly clean filters;
(j) If microbiological sampling is to be done, obtain sterile bottles and ice chests. Ice chests are recommended for all sample storage;
(k) Check the contents of the emergency first-aid kit.

7.5 FIELD MEASUREMENTS

7.5.1 Automatic monitoring

The use of one particular instrument requires that the water be pumped and that the measurements be made on shore. Other instruments use probes immersed in the water body and the measurements are made in situ. A more recent type is a self-contained, battery-operated instrument that can be operated as much as 300 m below the surface.

Currently, automatically measured parameters include pH, temperature, specific conductance, turbidity, dissolved oxygen, chloride, redox potential, stage, sunlight intensity and ultraviolet absorbance.

7.5.2 Field-measured parameters

Conductivity, pH, dissolved oxygen, temperature, turbidity, colour and transparency can change on storage of a sample, and should therefore be measured in the field as soon as possible after the sample collection.

The sample collector should also look out for any unusual features of the water body being sampled or any changes since previous sampling periods.

These qualitative observations might include unusual colour, odour, surface films and floating objects. Any special environmental conditions, such as rainfall, heavy winds, storm runoff, or ice break-up, should be noted.

7.5.2.1 pH measurement

In unpolluted natural waters, the pH is largely controlled by a balance between carbon dioxide, carbonate and bicarbonate ions. The concentration of carbon dioxide can be altered by exchanges at the air-water interface and by photosynthesis and decay processes. Changes in the pH are caused by acid rain, industrial wastes, mine drainage or leaching of minerals. The pH is an important criterion of the quality of water since it affects the viability of aquatic life and many uses of the water. Being temperature dependent, pH measurement must be strictly associated to the sample temperature at the sampling moment. Optimally, the pH is determined in situ, using a digital meter with a combined electrode permitting simultaneous temperature measurement.

The pH may also be determined colourimetrically by using pH indicators and buffer standards for visual or colourimeter comparison. This method is generally less accurate and is limited to waters with a low content of coloured substances and with little turbidity. In the field, the instrument should be recalibrated before each reading with appropriate buffer solutions and according to the instructions in the operating manual. The temperature of the buffer solutions and electrodes can be adjusted by submerging the bottles of buffer and electrodes in the water sample.

Extreme care must be taken to prevent the water from entering the buffer bottles. If the electrodes have not been used recently or have been allowed to dry for several days, they may require 10 to 20 minutes to stabilize. The meter should be protected from extreme temperature changes during measurement as these affect the stability of the electronic system and measurement accuracy.

When combined electrode assemblies have been stored dry for a long period, the glass membrane should be soaked in a 3 mol/l KCl solution for 12 to 24 hours before use. pH meters may have a probe-storage reservoir that should be filled with electrolyte. Glass electrodes that have not been conditioned before use may not stabilize properly and may require frequent recalibration.

If the pH meter shows a drift and the probe has been stored and correctly conditioned, the probe itself may require topping up with additional 3 mol/l KCl solution.

If there is persistent drifting, the electrode should be soaked in ammonium hydroxide. As with any piece of equipment, the probe should be protected from sludge, frost and rough handling at all times.

7.5.2.2 Conductivity measurement

Conductivity is an indicator of salt, acid and base non-organic concentration of ions dissolved in water. The relationship between conductivity and the concentration of dissolved solids is usually linear for most natural waters.

In situ conductivity measurement is preferable. Being temperature dependent, the conductivity meter should give a value for either a reference temperature (generally 20°C or 25°C) or the sample temperature, which must be recorded simultaneously. This is important to calculate and compare sample conductivity at a given reference time.

Before any measurements are taken, the sample containers and probe should be rinsed several times with the water sample. The water sample in which the pH was measured should not be used to measure the specific conductance, as KCl diffuses from the pH electrode.

The instrument should be recalibrated in the field before each reading. The KCl standard solutions, with the specific conductance closest to the values expected in the field, should be used. Equipment for measuring conductivity must receive the same care and maintenance required by all sensitive instruments. Accurate readings require that the meter be protected from sludge, shocks and frost.

The accuracy of measurement will depend upon the type of instrument, the way in which it has been calibrated and the actual conductivity value of the sample. If care is taken in selecting and calibrating the instrument, an uncertainty of ±5 per cent of full scale should be possible over a temperature range of 0°C to 40°C with automatic temperature compensation.

7.5.2.3 Dissolved-oxygen measurement

Dissolved-oxygen concentration is important for the evaluation of surface water quality and of waste treatment process control.

There are two methods for dissolved-oxygen measurement: the first is in situ by using a polarographic or potentiometric (oxymeter) probe. The second is by using a Winckler chemical analysis. In the Winckler method the addition of reagents (Mn^{++} solution and basic iodure solution) in the sample at the moment of its grab permits its oxygen fixation. Analysis will then be performed in the laboratory on a sample preserved by light. There is also a field method based on the same principle, namely, the Hach method using pre-dosed reagents.

As concentrations may show large changes during the day, in situ time measurements are advisable.

For the chemical method, three water samples should be collect with the dissolved-oxygen sampler (7.3.5.2). Measurement of the dissolved-oxygen concentration of the samples is done by using a dissolved-oxygen meter or a Winkler chemical analysis. The recorded dissolved-oxygen value should be the average of at least two readings that are within 0.5 mg/l of each other.

In the electrochemical methods the probe responds to activity of oxygen, not concentration. Freshwater saturated with oxygen gives the same reading as saltwater saturated with oxygen at the same pressure and temperature, although the solubility of oxygen in saltwater is less. Thus, salinity, temperature and atmospheric pressure should be considered when sampling.

In the Winkler chemical method there are interferences when samples are highly coloured or turbid, or contain readily oxidizable or other interfering substances. This method is largely used in laboratories for its accuracy in measuring dissolved-oxygen concentration.

The probe method can be used when results are within ±0.5 to 1.0 mg l^{-1} of the true value and are sufficient for the purposes of the study. If the sample has a relatively high dissolved-oxygen concentration, the accuracy is adequate, but in some cases the dissolved-oxygen concentration is shown to be very low; then it is important to use a new and carefully calibrated probe.

7.5.2.4 Temperature measurement

Temperature measurements may be taken with a great variety of thermometers. These include alcohol-toluene, mercury-filled, bimetallic strip or electrical thermometers. The last category includes thermocouples and less portable varieties, such as thermistors, quartz and resistance thermometers. Some meters, such as those used to measure dissolved oxygen, pH, Eh and specific conductance, have temperature-measuring capabilities.

Before its use, the thermometer is rinsed with a portion of the water sample. The thermometer is immersed in the sample for approximately one minute or until the reading stabilizes. The thermometer must not be placed in any of the sample bottles being shipped to the laboratory. The value should be recorded in degrees Celsius on the field sheet.

In general, the accuracy of water-temperature measurements of 0.1°C will not be exceeded. However, in many circumstances, an uncertainty of 0.5°C can be tolerated and there are many instances where statistical temperature data are quoted to the nearest 1°C. Thus, it is important to specify the operational requirements so that the most suitable thermometer can be selected.

7.5.2.5 Turbidity measurement

Turbidity is an optical measure of suspended sediment such as clay, silt, organic matter, plankton and microscopic organisms in a water sample. Turbidity virtually affects all uses of water and adds to the cost of water treatment. Whenever possible, turbidity should be measured in situ. Turbidity can be measured by visual methods (in Jackson turbidity units or JTU) or nephelometric methods (in nephelometric turbidity units or NTU). Using the Jackson Candle Turbidimeter, the distance through the suspension at which the outline of the standard candle becomes indistinct is compared with standard suspensions.

Nephelometric methods are preferred because of their greater precision, sensitivity and application over a wide turbidity range. They measure light scattering by the suspended particles. However, instruments of different design may give different results for the same sample. Colour in the sample as well as variations in the light source can cause errors. Both problems can be minimized by using an instrument that simultaneously measures the scattered and transmitted light, with both scattered and transmitted beams traversing the same path length.

To operate the turbidity meter, calibration curves for each range of the instrument should be prepared by using appropriate standards. At least one standard in each range to be used should be tested, making sure that the turbidity meter gives stable readings in all sensitivity ranges. The sample should be shaken vigorously before analysis. Readings should always be made after the same time period following the homogenizing of the sample (for example, 10 seconds) to ensure uniform data. It is important to pour off the sample quickly and to measure the turbidity of the sample in triplicate.

The performance of a given turbidimeter will depend on the frequency of calibration with a formazin standard and the way that the sample is presented to the instrument. As a general guide, nephelometers used under laboratory conditions should be accurate to within ±1 formazin turbidity unit (FTU) in the range 0 to 10 FTU, and to ±5 FTU in the range 0 to 100 FTU at 95 per cent confidence level. The uncertainty of absorption meters will vary considerably, but should give at least ±10 per cent of full scale for any given range of turbidity.

In practice, the performance of turbidimeters depends, to a large extent, on their optical configuration and, in the case of instruments that accept a flowing sample and give a continuous reading, on their ability to withstand fouling of optical surfaces by algal growth and sediment build-up, which would otherwise result in calibration drift and insensitivity.

7.5.2.6 Colour measurement

The true colour is observed after filtration or centrifugation. Colour results from the presence of metallic ions, humus and peat materials, plankton and industrial wastes. Colour is important for potable water supplies, washing or processing, or recreational purposes.

The hues ordinarily present in natural waters can be matched by mixtures of chloroplatinic acid and cobaltous chloride hexahydrate. Because this method is not convenient for field use, colour may be obtained by visually comparing standard glass colour discs with tubes filled with the sample.

Waters mixed with certain industrial wastes may be so different in hue from platinum-cobalt mixtures that comparison is inappropriate or impossible. In this case, a filter photometer may suffice, although a double-beam spectrophotometer would be preferable if the samples can be taken to the laboratory.

7.5.2.7 Transparency measurement

Transparency of water is determined by its colour and turbidity. A measure of transparency can be obtained from depth in metres at which a 20- to 30-cm diameter disc – called a Secchi disc and usually painted in black and white quadrants – disappears when lowered slowly and vertically into the water. Standard type on white paper is sometimes used instead of the disc. The measurement is usually made in lakes and other deep-water bodies and is useful in assessing biological conditions.

7.5.2.8 General summary of field procedures

Regardless of the specific parameters of interest, a routine should be followed at each sampling station. The following is a general summary of procedures to be followed at each station:

(a) Calibrate meters;
(b) Standardize sodium thiosulphate when using Winkler analysis for dissolved oxygen;
(c) Run field or in situ measurements for pH, conductivity, dissolved oxygen, temperature and turbidity;
(d) Rinse all bottles with sampled water except for those that contain preservatives or those used for dissolved oxygen and bacteria analyses;
(e) Collect and preserve samples according to the instruction manual;
(f) Complete field sheet accurately according to the instruction manual;
(g) Put bottles in appropriate shipping containers;
(h) Label boxes and complete field sheets with all required information.

7.6 BIOMONITORING AND SAMPLING FOR BIOLOGICAL ANALYSIS

Environmental monitoring is mainly based on physical-chemical analysis techniques to evaluate the concentration of pollutants, sediments and living organisms in water. The major inconvenience of these methods may be their lack of information about the actual chemical impact on living organisms. Furthermore, certain groups of toxic pollutants are not detectable. This occurs because:

(a) These molecules influence living organisms at a concentration below detection limits;
(b) There may be completely new molecules;
(c) The evolution of these toxic pollutants in the environment is little known (in this case the problem is to identify the by-products to be analysed).

Thus, the great variety of potential pollutants in the monitoring media makes these methods highly costly. Lastly, if chemical analyses inform about the existence or non-existence of a pollutant in different ecosystem compartments (water, soil, sediments or organisms), they are in any case insufficient to predict the actual impact of the toxic substances on the organism, since the numerous interactions between pollutants and pollutants/organism have not been considered. Biological analyses can integrate the interactions between all the present pollutants and organisms and can diagnose the pollution impact on the organisms living in the ecosystem more realistically.

Biomonitoring is the study of the living response to all the degrees of biological organization (molecular, biochemical, cellular, physiological, histological, morphological and ecological) to pollutants. This definition (McCarthy and Shugart, 1990) identifies the following levels of observations:

(a) At the intra-individual level a biomarker is the biological response detected at a level below the individual to a substance present in the environmental product (van Gestel and van Brummelen, 1996). This response measured in an organism or in its products shows a change in a normal state, for example, the modification of an enzymatic activity owing to a defence process in the organism. Biomarkers are also specific molecular, biochemical, physiological, histological and morphological changes in animal and vegetal populations observed after exposure to pollutants;

(b) At the level of individuals or organisms a bioindicator is performed by measuring the vital functions of a biological entity which, owing to its ecological specificity, reacts to a pollutant with a relevant specific modification of its vital functions (Kirschbaum and Wirth, 1997), for example, an alteration in the growth of a microinvertebrate organism;

(c) At the level of populations and settlings, the hydrobiological analysis obtains integrative data on global water quality. There are biological indexes permitting the study of all or parts of the species settled in an ecosystem and the variations of their composition and structure owing to an anthropic factor. It is thus possible to define quality classes by the normalized inventory of certain species. For example, the Environmental Biological Index uses macroinvertebrate fauna as an environmental compartment integrator; a standardized sampling considering different types of settling habitats shows the ecosystem quality by the presence or absence of faunistic indicator groups.

In the current phase of biological monitoring, the studies using biomarkers concern the research of new methods to evaluate the health of organisms and practical applications to a larger amount of comproved techniques of pollution monitoring. Routine biomarker methods are still limited, but current studies show that it is already possible to detect polluted areas considering the health of organisms living there. The methods based on the studies at the organism or population level are used in biomonitoring network. Microbiological and macrobiota sampling will soon be developed.

Furthermore, there are also methods concerning the global evaluation of the environmental river self-epuration capacity. BOD, developed in this chapter, is the most widely used method.

7.6.1 Microbiological analysis

The presence of living fecal coliform bacteria indicates inadequately treated sewage. The complete absence of coliforms, and especially of fecal coliforms, is mandated by the World Health Organization for any drinking water supply. Other micro-organisms responsible for human diseases are sometimes found in water, for example the cholera and typhoid agents, salmonella, pseudomonas, and certain single-celled animals, such as those that cause amoebiasis.

In order to accurately reflect microbiological conditions at the time of sample collection, it is very important that all water samples submitted for microbiological analysis be collected as aseptically as possible.

Microbiological samples are usually collected in sterile 200- or 500-ml wide-mouthed glass or non-toxic plastic bottles with screw caps. Plastic containers should be checked to make sure that they do not shed microscopic particles capable of confusing some kinds of bacterial counts. Metal and certain rubber containers may exert a bacteriostatic effect. If capped, the bottle cap should have an autoclavable silicone rubber liner. If tapered, the bottle mouth should be covered with sterile heavy-duty paper or aluminium foil secured with either string or an elastic band.

Whenever possible, water samples should be analysed immediately after collection. If immediate processing is impossible, then samples should be stored in the dark, in melting ice. Storage under these conditions minimizes multiplication and die-off problems up to 30 hours after collection. Samples should never be frozen. If samples are suspected of containing concentrations greater than 0.01 mg l^{-1} of heavy metals, such as copper, nickel or zinc, their bacteriostatic or bactericidal effects should be minimized by the addition of 0.3 ml of a 15 per cent solution for each 125 ml of sample of ethylene diamine tetra-acetic acid (EDTA) (Moser and Huibregtse, 1976). Residual chlorine should be destroyed by the addition of 0.1 ml of a 10 per cent solution of sodium thiosulfate for each 125 ml of sample.

7.6.2 Macrobiota

There are several categories of multicellular species that may be monitored for a number of different reasons. Fish, as the top of the aquatic food chain, are indicative of a variety of water quality conditions, dependent on their type and age. Benthic macroinvertebrates (organisms living on or near the bottom that are retained by a standard sieve) are indicators of recent pollution events because of their low mobility and sensitivity to stress. Periphyton are sessile plants, growing attached to surfaces, and those that grow in the mat attached to it are some of the primary producers of aquatic organic matter, particularly in shallow areas. Macrophytes are large plants, often rooted, that cover large areas in shallow water and may interfere with both navigation and recreational uses of a water body. Plankton are small free-floating plants and animals. Phytoplankton are primarily algae whose growth is an indirect measure of, among other things, the concentration of nutrient chemical constituents. Zooplankton are found at all depths in both lentic and flowing waters.

Many of these organisms can be troublesome in water treatment. For example, algae clog filters, consume extra chlorine, adversely affect odour and taste of water, and some are toxic. Other species may be carriers of disease-causing organisms, such as the snails that carry guinea worm larvae or schistosomes.

Fish can be collected actively, with seines, trawls, electro-fishing, chemicals, and hook and line, or passively, with gill nets, trammel nets, hoop nets and traps. Macroinvertebrates may be sampled qualitatively by many methods, depending on their habitats and other parameters. In addition to nets, two methods are multiple-plate samplers and basket samplers. These are left suspended in place by floats for periods of four to eight weeks, and then are carefully raised to the surface with a net underneath for dislodgement of the specimens.

Plankton can be collected by using the water samplers described above in 7.3. There are also specially designed samplers, such as the Juday plankton trap, which encloses at least 5 l of sample at the desired depth and filters out the plankton. It is rather expensive and awkward to handle from a boat. Zooplankton require large samples, and a metered nylon net can be employed. Periphyton can be sampled by exposing anchored or floating slides at the site for at least two weeks.

For macrophytes, a garden rake can be used in shallow water and dredges can be used in deeper water. From a boat, a cutting knife on the end of a pole or a simple grapple can be used. For some purposes, the self-contained underwater breathing apparatus has been found to be useful.

It is recommended that a suitable stain such as rose bengal be added before any fixatives. At a later date, the preserved animals can be picked out by personnel with less biological training because the colour causes them to stand out against the background. Tables recommending methods for the preservation of specimens of macrobiota are included in Table I.7.1. Some practitioners prefer the use of lugol solution rather than formaldehyde for periphyton and planktons.

7.6.3 Biochemical oxygen demand

The discharge of polluting organic matter into a water body instigates a natural purifying action through the process of biochemical oxidation. Biochemical oxidation is a microbial process that utilizes the polluting substances as a source of carbon, while consuming dissolved oxygen in the water for respiration. The rate of purification depends on many conditions, including the temperature and the nature of the organic matter. The amount of dissolved oxygen consumed by a certain volume of a sample of water for the process of biochemical oxidation during a period of five days at 20°C has been established as a method of measuring the quality of the sample, and is known as the biochemical oxygen demand test or BOD. Oxidation is by no means complete in five days and for some purposes longer periods of incubation may be used. The incubation period may be indicated by a suffix, for example, BOD_5 or BOD_{20}, and the results are expressed as mg of oxygen per litre of sample.

BOD is defined as the total amount of oxygen required by micro-organisms to oxidize decomposable organic material. The rate of biochemical oxidation is proportional to the remaining amount of unoxidized organic material. Thus, the BOD test is used to estimate the amount and rate of de-oxygenation that would occur in a watercourse or lake into which organic material is discharged. However, the predictions of the effects of such discharge are more complicated and may involve many other factors not involved in the

Table I.7.1. Techniques generally suitable for the preservation of samples

Biological analysis. The biological parameters to be determined are generally numerous and may sometimes vary from one biological species to another. For this reason, it is impossible to draw up an exhaustive checklist of all the precautions that should be taken to preserve samples for this type of analysis. The information below, therefore, only relates to certain parameters generally studied for various animal or vegetal groups. It should be noted that before carrying out any detailed study, it is essential to choose the parameters of interest.

1	*2*	*3*	*4*	*5*	*6*
Counting and identification					
Benthic macroinvertebrates	Plastic or glass	Addition of ethanol	Laboratory	1 year	
Fish	Plastic or glass	Addition of 10% (m/m) formaldehyde, 3 g of sodium borate decahydrate and 50 ml of glycerol per litre	Laboratory	1 year	This analysis should preferably be carried out as soon as possible
Macrophyton	Plastic or glass	Addition of 5% (m/m) formaldehyde	Laboratory		
Periphyton	Plastic or opaque glass	Addition of 5% (m/m) neutral formaldehyde and storage in the dark	Laboratory	1 year	
Phytoplankton	Plastic or opaque glass	Addition of 5% (m/m) neutral formaldehyde or mentholate and storage in the dark	Laboratory	6 months	
Zooplankton	Plastic or glass	Addition of 5% (m/m) formaldehyde or a lugol solution	Laboratory		
Fresh and dry mass					
Benthic macroinvertebrates					Do not freeze to –20°C
Macrophytes	Plastic or glass	Cooling to between 2°C and 5°C	On site or in the laboratory	24 hours	The analysis should be carried out as soon as possible and not later than 24 hours.
Pheriphyton Phytoplankton Zooplankton Fish			On site		
Mass of ash					
Benthic macroinvertebrates		Filtration and cooling to between 2°C and 5°C	Laboratory	6 months	
Macrophyton	Plastic or glass	Freezing to –20°C	Laboratory	6 months	
Periphyton		Freezing to –20°C	Laboratory	6 months	
Phytoplankton		Filtration and freezing to –20°C	Laboratory	6 months	
Calorimetry					
Benthic macroinvertebrates Phytoplankton Zooplankton	Plastic or glass	Cooling to between 2°C and 5°C, then filtration and storage in a desiccator	Laboratory	24 hours	The analysis should preferably be carried out as soon as possible and in all cases with 24 hours.
Toxity tests	Plastic or glass	Cooling to between 2°C and 5°C Freezing to –20°C	Laboratory Laboratory	36 hours 36 hours	The preservation period will vary according to the method of analysis.

determination of BOD. For example, suspended organic material can be deposited onto a stream bed in a slow moving stream just downstream from the source of discharge, where it may have a considerable effect on the local dissolved oxygen content. The presence of benthos, rooted plants and planktonic algae also influence the dissolved oxygen regime on a daily basis.

Serious complications in the BOD test can also occur as a result of the presence of nitrifying bacteria that will oxidize ammonia and organic nitrogen compounds to nitrite and nitrate.

Industrial effluents may also present problems because of potentially high concentrations of pollutants, which may suppress biochemical oxidation in the receiving water under natural conditions. In these circumstances, the sample may have to be diluted with pure water and "seeded" with sewage effluent that contains the active micro-organisms required to start the biochemical oxidation process. Special sample preparation techniques may have to be developed to suit the sample to be tested.

7.6.3.1 Methods of measurement

Several methods have been developed for the measurement of BOD. The one most commonly used is the dilution method, but manometric techniques, while still mainly used for research, may have advantages in some circumstances, for example the control of sewage effluent. Ideally, the sample should be analysed immediately after it has been taken from the effluent, watercourse or lake. If this is not possible, the sample must be kept at a temperature of 3° to 4°C to slow down the biochemical oxidation processes. If BOD of a sample is estimated to be greater than about 7 mg l^{-1}, appropriate dilution and/or seeding of the sample are necessary. An excess of dissolved oxygen must be present in the sample at the end of the test period for the BOD value to be valid.

BOD is calculated from the measurement of volumetric dilution of the sample and the difference between the dissolved-oxygen concentrations of the sample (7.5.2.3) before and after a five-day incubation period. During this period, a temperature of 20°C should be maintained, and atmospheric oxygen should be excluded from the sample, which should be kept in the dark to minimize the effect of photosynthetic action of green plants. However, the oxygen consumed by the respiration of algae is included in the test. For samples in which nitrification may occur during the test, allylthiourea (ATU) is added to the sample prior to incubation. In this case, the resulting apparent BOD is indicative of carbonaceous polluting matter only. The rate of biochemical oxidation can be estimated on the basis of incubating five identical BOD samples and measuring the dissolved oxygen in the first bottle on day 1, the second bottle on day 2, the third bottle on day 3, the fourth bottle on day 4, and the fifth on day 5. The logarithm of BOD should plot against time as a straight line. Extrapolation of the straight line to ultimate time results directly in an estimate of the ultimate carbonaceous BOD, which is a measure of the total amount of oxygen required to oxidize decomposable organic material.

7.6.3.2 Accuracy of measurement

The BOD test is rather inexact. If statistical significance is to be made of the results, several samples must be diluted and incubated (and seeded, if necessary) under identical conditions, and an average BOD calculated. To achieve higher accuracies, it has been suggested that the manometric test should replace the dilution method. It should be borne in mind that the two methods are not always directly comparable (Montgomery, 1967). The manometric method can give an indication of the biological oxidizability of a sample in a period shorter than five days.

7.7 FIELD FILTRATION AND PRESERVATION PROCEDURES

7.7.1 Filtration

Sample filtration is recommended for separation of dissolved from particulate matter. Centrifuging requires more equipment, settling requires more time, and both cannot be easily calibrated and may increase contamination hazards. The filtration should be carried out in the field during or immediately after sample collection and must be followed by appropriate sample preservation procedures.

The total concentrations of metals may be determined by using a second unfiltered sample collected at the same time. This sample will undergo an acid digestion in the laboratory permitting particulate dissolution.

Samples requiring analysis for organic constituents are filtered immediately after collection by using a glass fibre filter or a metal membrane. The filtrate may be analysed for dissolved organic constituents, and the filtre supporting the particulate fraction is available for particulate-organic analysis.

The adsorption of dissolved substances on the filter material can be a serious problem.

The best materials to be used for mineral substances are organic filters (polycarbonate, cellulose acetate or Teflon) and glass fibre filters for organic compounds.

The filter and filtration apparatus require laboratory pretreatment and should be rinsed with a portion of the collected sample before the filtrate is collected, by discarding the first 150 to 200 ml of filtrate. Either an electrical or a manual pump must be used to create the vacuum in the filtration apparatus. If an electrical pump is employed, filtration will require access to electrical services or the operation of a mobile power unit. Vacuum may cause changes in the pH due to loss of carbon dioxide, and result in the precipitation of some metals. For this reason and to reduce losses due to adsorption on the walls of the container, metal samples are often acidified.

7.7.2 Preservation techniques

Between the time that a sample is collected in the field and analysed in the laboratory, physical, chemical and biochemical changes may take place. Consequently, this time should be minimized as far as practicable, or sample preservation must be practised.

For several determinants, preservation is not possible and the measurements must be made in the field. Even when the constituent is reasonably stable, it is usually necessary to preserve the samples. This is done by various procedures, such as keeping the samples in the dark, adding chemical preservatives, lowering the temperature to retard reactions, freezing samples, extracting them with different solvents, or using field column chromatography.

7.7.2.1 Containers

The use of appropriate containers is very important in preserving the integrity of the sample especially when constituent concentration is low. Specifications are generally provided by laboratories. Many publications contain recommendations on which type of container should be used for particular cases (Clark and Fritz, 1997).

The major types of container materials are plastic and glass. Borosilicate glass is inert to most materials and is recommended when collecting samples to be analysed for organic compounds. Polyethylene is inexpensive and adsorbs fewer metal ions. It is used for samples that will be analysed for inorganic constituents. Polyethylene containers should not be used to trace organic samples, such as pesticides and some volatile substances that can diffuse through plastic walls. Light-sensitive samples require opaque or non-actinic glass containers. Narrow-mouthed bottles with pointed glass stoppers are used for dissolved gases. Containers for microbiological samples must withstand sterilization.

For tracking elements, only low- or high-density polyethylene (LDPE and HDPE) should be used. Today disposable containers are available. Before use, they must be pre-decontaminated. They must be kept, for at least 24 hours, in an ultrapure 10 per cent solution of HNO_3, then rinsed in ultrapure (18.2 MΩ) water and preserved in polyethylene bags until their field use (Pearce, 1991).

Bottle caps are a potential source of problems. Glass stoppers may seize up, particularly with alkaline samples. Cap liners other than Teflon may introduce contaminants or absorb trace samples. The smaller the concentrations in the sample of the species to be determined, the more important these aspects become.

7.7.2.2 Chemical addition

This method is used for most dissolved metals and phenoxy acid herbicides. Some samples for biological analysis also require chemical preservation.

As a general rule, it is preferable to use relatively concentrated solutions of preserving agents. Corrections for the dilution of the sample by the small volume of preserving agent will then be small or negligible.

Potential interference of the preservative with the analysis requires that procedures be carefully followed. For example, an acid can alter the distribution of suspended material and can lead to dissolution of colloidal and particulate metals. Thus, the order of first filtration and then acidification becomes very important.

7.7.2.3 Freezing

When analysis is impossible in a reasonable period of time, freezing is recommended for the analysis of main anions, that is, chloride, sulfate and nitrates. However, this is not a general preservation technique because it can cause physical-chemical changes, for example, the formation of precipitates and loss of dissolved gases that might affect the sample composition. In addition, solid components of the sample change with freezing and thawing, and a return to equilibrium followed by high-speed homogenization may be necessary before any analysis can be run. Water samples should never be frozen in glass bottles.

7.7.2.4 Refrigeration

Refrigeration at 4°C is a common preservation technique. In some cases it may affect the solubility of some constituents and cause them to precipitate. Refrigeration is often used in conjunction with chemical addition.

7.7.2.5 Practical aspects of preservation

An important aspect of preservation is adherence to a consistent routine to ensure that all samples requiring preservation receive immediate treatment. This is particularly important when a chemical preservative is added, as such additions may not produce an easily detectable change in the appearance of the sample. It may be advisable to mark or flag each preserved sample to ensure that none is forgotten or treated more than once.

Safe and accurate field addition of chemical preservatives also requires special precautions. Pre-calibrated and automatic pipettes ensure accurate field addition, as well as eliminating the safety hazard of pipetting acids by mouth. It is often convenient to add the preservative in the laboratory before the sample containers are taken to the field. Another alternative is to use colour-coded or labelled, sealed vials containing pre-measured preserving agents. Although more expensive, this method has the advantage of simplifying the field procedure and reducing the possibility of error and contamination.

7.8 REMOTE-SENSING AND SURFACE-QUALITY WATER

Teledetection permits the characterization of the spatial and temporal changes obtainable by other methods. However, it is not accurate in terms of local ground measures. Furthermore, it should be implemented with satellite image readings to interpret images in water quality and soil measurement terms. Remote-sensing application for suspended matter evaluation is discussed earlier in Chapter 5. More detailed information is provided on applications such as vegetation characterization, salinity and water temperature.

Satellites can be divided into two groups, depending on their energy source. Passive satellites need sunlight to capture object images on the Earth’s surface. They generally operate in the visible and infra-red domain of EMS and supply the so-called “optic” images. Active satellites have their own energy source. They operate in the microwave domain of EMS and supply the so-called “radar” images.

Furthermore, satellite images can be differentiated according to four basic criteria:

(a) Range gating corresponding to pixel size. There are small sized (1 km or more, such as NOAA, SPOT vegetation or meteorological images), medium (20 m or more, such as Landsat MSS and TM or SPOT 1 to SPOT 4 images) or outsized range gating (10 m or less, such as in SPOT 5 or IKONOS);
(b) Spectrum gating corresponding to the wavelength in which images have been taken;
(c) Passage frequency of the satellite;
(d) Radiometric gating corresponding to the detector ability to catch the received radiant emittance.

The choice of satellite image is determined by many factors. First, the size of the studied area should be considered. It will not be possible to study a 20-km^2 marsh with a NOAA image based on low-range gating. Spectrum gating will be chosen according to the programme objectives. For example, an optical image is advisable to study water turbidity. Finally, the equalization between the time variables of the studied phenomenon and the satellite passage frequency over the studied area are required.

7.8.1 Water-quality study in the visible and infra-red domain

From the visible domain to the near IR, the radiometric response of pure water is like that of a black body absorbing the whole incident radiation. This well-known property is used to easily locate the presence of water on a satellite image.

Different factors, such as water salinity and turbidity, soil composition or vegetation presence, alter water radiometric response, which can therefore be used to inversely characterize these factors.

The best positive correlation between radiometric response and turbidity is in the green range (Bonn, 1993). This will indirectly provide indications on salinity. In fact, salinity and turbidity are generally inversely correlated. When salinity arises, it results in flocculation followed by sedimentation of suspended matter and the lowering of the turbidity of the water.

Water radiometric response in the near IR may be perturbed by suspended matter and also by a shallow bottom (Chuvieco, 2000). For shallow waters, absorption is low and reflectance is large (due to high bottom reflectance). However this effect is complex, as soil radiometric behaviour is influenced by its chemical composition, texture, structure and humidity. Therefore, a clay soil, for example, will have quite a low reflectance, compared with a sand soil. The soil reflectance range is very large between light soils (sand, limestone or even gypsum), highly reflecting solar radiation, while dark soils (clay, rich in organic matter) absorb nearly the full amount of radiation (Bonn and Rochon, 1993).

In the radiometric domain, vegetation reflectance is reduced in the visible spectrum, but is very high in the near IR. As regards vegetation, low response in the visible range results from strong absorption of chlorophyll, especially in the red range, whereas the high response in the near IR is due to the internal cell structure of leaves. Thus, to study the presence of vegetation in shallow waters it is advisable to use optical images (Shutko, 1986, 1990; Gross and others, 1987).

The assessment of chlorophyll quantity in the ocean and estuaries has been carried out from different images, especially Coastal Zone Colour Scanner (CZCS) or AVHRR images (WMO, 1993). This assessment is limited to cases where suspended matter concentration is low enough not to mask the reflectance corresponding to that of chlorophyll (Ritchie and others, 1992). Macrophytes and aquatic vegetation can be generally studied following these basic principles (Ackleson and Klemas, 1987).

7.8.2 Water-quality study in the microwave domain

In waters, the microwave domain permits a certain penetration. Superficially it is possible to differentiate a rough from a smooth surface by a lambertian or symmetric response, respectively. For example, a radar image may be used if roughness is due to the presence of waves. These applications have also been exploited to detect surface anomalies such as those due to indiscriminate oil discharge. It has proved, both theoretically and practically, that microwave radiometry can be used to study salinity and general water mineralization (Shutko, 1985, 1986, 1987). In fact, microwave emissivity is sensitive to water conductivity variations, and thus to water composition.

Teledetection in the thermal IR domains and microwave radiation can be used to evaluate surface water temperature (examples in Engman and Gurney, 1991). Microwave radiation is less sensitive to atmospheric conditions and thus it will be more often used, but its resolution is rough compared with that of the IR (Shutko, 1985, 1986).

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CHAPTER 8

SAFETY CONSIDERATIONS IN HYDROMETRY

8.1 GENERAL PRACTICES

The WMO technology transfer system, the Hydrological Operational Multipurpose System (HOMS), in operation since 1981, offers a simple but effective means of disseminating a wide range of proven techniques for use by hydrologists. Particular reference is made to section A00 of the HOMS Reference Manual, which covers policy, planning and organization. This chapter, on safety considerations in hydrometry, complements preceding chapters that provide an overview of the hydrological instruments and methods of observation, by proposing safety measures needed to support the operating activities of hydrologists.

Hydrological measurements are made under an extremely wide range of conditions, many of which are potentially hazardous to the personnel making them. Knowledge of the hazards and the means by which they can be minimized are essential for hydrological personnel. A number of agencies have produced detailed and informative safety manuals. Familiarization with this material is highly recommended to hydrologists and technicians.

Each State may have its own safety standards and practices as well as laws and regulations governing safety. Additionally, at particular sites, there may be specific safety precautions which hydrological personnel would be expected to observe. Many of these are outlined in this chapter.

Each member of a hydrometric field-team has the responsibility for his or her own personal safety and that of the other team members in carrying out his or her work. Organizations have the responsibility to promote an awareness of hazards and work practices needed to minimize risks, and to provide appropriate safety equipment and training.

8.2 SAFETY AT RECORDING STATIONS

8.2.1 Access

Well-constructed footpaths, steps, ladders and the like are essential for safety on steep riverbanks. These need to be constructed for safe access in wet weather and possibly in the dark. When construction of a station begins, the access should be completed first.

8.2.2 Platforms

High platforms and catwalks should have a non-slip surface, such as fine wire mesh fastened over timber planks. Handrails should also be fitted.

8.2.3 Wells

Some water-level recording stations have deep wells that must be entered occasionally for maintenance. Hazards exist owing to the possibility of falling and the presence of gases. All wells should have at least a simple rope, pulley and winch system installed so that a person can be rescued from the bottom of the well.

Persons descending into wells that are deep or are in any way suspected to contain gas must wear a safety harness attached to a rescue system, with one or more people in attendance at the top. A safety helmet should also be worn.

A number of gases, including carbon dioxide, methane and hydrogen sulphide, may be present in a well. They are produced from decomposing organic material and may displace air, leading to an oxygen deficiency as well as toxicity and flammability. These dangers can occur with quite low concentrations, and reaction to the gases may be quite rapid, with a person becoming unconscious after only one or two inhalations of a toxic gas.

Precautions include proper ventilation in all wells over 6 m in depth, opening wells for ventilation prior to entry, forbidding flames or smoking, use of gas monitoring equipment, and the routine use of safety harnesses and rescue equipment. All efforts should be made to exclude or remove organic matter from wells. The hazards of slipping can be minimized by having properly constructed ladders and by maintaining all equipment in good condition.

8.3 SAFETY PRECAUTIONS WHEN WORKING FROM BRIDGES

The main hazards in carrying out measurements or sampling from bridges are getting struck by passing traffic or being tipped over the side of the bridge by undue force or weight on the suspended equipment.

8.3.1 Traffic hazards

Bridges with a pedestrian lane may provide a good margin of safety. In other circumstances, it is imperative to warn motorists with adequate signs and, if practical, flashing lights. Personnel should wear fluorescent or brightly coloured clothing, and portable traffic markers may be deployed to shift traffic flow away from the work area. If it is necessary to interface with traffic, arrangements should be made with the local authorities. In areas where there are FM radio stations, it is important to announce the schedules of the hydrological activities, so that the public may be made aware.

8.3.2 Hazards from suspended equipment

The potential leverage on equipment, such as gauging frames, indicates that they are prone to being tipped over the side of the bridge if the suspended equipment should become caught on river-borne debris or on boats passing below. Extra care should be taken against these dangers during floods.

Gauging cranes or frames need to be suitably counterbalanced or tied down. The overturning moment of vehicle-mounted cranes should be calculated and shear pins incorporated in the equipment, if necessary, to prevent capsizing. Over navigable water, the presence of all cables should be indicated by the attachment of marker flags.

8.4 SAFETY PRECAUTIONS WHILE WADING

8.4.1 General

Where it is possible to wade streams, hydrological measurements may be made more simply and directly than by other means. However, it becomes hazardous when the depth or velocity, or both, are excessive. Personnel must not be obligated to wade streams in situations where they feel unsafe. Experience and confidence are important factors, but must be tempered with sensible caution.

8.4.2 Assessing the situation

Personnel need to exercise caution and be experienced enough to decide whether wading should be carried out in a particular situation. As a general guide, if the product of the depth in metres and the velocity in metres per second exceed 1.0, the stream is unlikely to be safe to wade. A person's build and attire will influence this decision. Waders have more drag than bare legs or wetsuits.

8.4.3 Wearing of life jackets

Correctly fastened life jackets of an appropriate size and design should generally be worn in flowing water above crotch level, where there is need to enter such water or where conditions could become hazardous.

8.4.4 Safety lines and taglines

When making discharge measurements, a rope or line strung across the river can be useful as a support. It can also serve as a line for measuring distance and should be securely anchored at both ends to sustain the weight and drag of a person against the flow of the river.

8.4.5 Wading technique

One should select a crossing with negotiable depths, velocities and bed material, plan a route diagonally downstream, and walk across with short steps, facing the opposite bank, and side-on to the current. It can be helpful to use a wading rod (without current meter) on the upstream side to probe the depth and provide support. It is preferable to brace against the current, remain calm and not hurry. If the crossing becomes too difficult, one should retreat, possibly by stepping backward until it is possible to turn around, and perhaps try an easier crossing.

8.4.6 In case of mishap

If one begins to be swept downstream, one should go with the current and head towards the bank, propelling oneself with the arms outstretched and pushing with the feet. If the bed is rocky, the natural reaction to put the feet down should be avoided as they may be caught between the rocks. If this occurs, a person can easily be pushed underwater by the current with fatal results.

If the water is deep and it is necessary to swim some distance, waders may need to be removed. The best way is to work them down to the hips and pull the feet out one at a time. One should avoid turning them inside out and should refrain from this operation where the water is shallow and the waders are likely to become snagged. Wader straps should be fastened in such a manner that they can readily be undone.

It is possible to trap air in waders so that they aid buoyancy, either by wearing a belt tightly fastened around the waist or by quickly assuming a floating position on one's back with the knees drawn up.

8.5 SAFETY PRECAUTIONS WHILE WORKING FROM BOATS

8.5.1 General

Many types of boats are used for hydrological purposes, each having their own safety requirements. These must always be observed, as boating is inherently dangerous. The boat operator must be familiar with all operating and emergency procedures, and all regulations governing the intended operations. These may include testing the lights of the boat, watching the weather and equipping the boat with appropriate clothing for variable weather conditions, a radio and emergency supplies. Alcohol or drugs should never be consumed during boat operations. Craft must be in good repair, adequate for the conditions that could be encountered, and must not be overloaded.

8.5.2 Life jackets and safety equipment

Life jackets must be worn at all times in small craft. In larger craft, there must be a sufficient number of life jackets on board for all passengers and crew.

Each boat must carry a full inventory of safety equipment that is appropriate to the type of craft and the conditions that could be encountered. These items may include all or some of the following: life raft, flares, lifebelts, bailer, bilge pumps, safety harnesses and survival equipment. Suitable radio communication equipment should be installed whenever practical. Each boat must have a rope attached to the bow for mooring and handling, as well as an adequate anchor and sufficient rope for the bottom conditions and depths expected to be encountered. Auxiliary motive power and fuel should be on board if at all practical.

8.5.3 Use of taglines

Measuring lines or taglines are frequently used for measuring the distance across a river. These need to be of an adequate size and type of material to prevent stretch and hold the necessary flags. However, the lighter the cable, the less tension is necessary in its rigging, and thus handling will be easier and safer.

Other lines may be rigged to moor the boat at the desired measurement points, and the same factors apply. Depending on the current, these may need to be rather more substantial. All lines must be flagged with sufficient large, brightly-coloured markers across navigable waters at intervals that make the line very evident to river users. Colour itself must not be relied upon, as many people are colour-blind. Where possible, boats working with such lines should be equipped with a bright flashing light. Appropriate local authorities and all likely river users should be notified of the hazards.

Such lines may not be left unattended, and on-site personnel should be equipped with wire cutters to be used, if necessary, to prevent an accident.

8.5.4 Use of dinghies

In rivers, one should row using the ferry-glide technique, heading diagonally upstream into the current. The rower is then facing in the direction of travel downstream, and steerage around any obstacle can be accomplished.

Personnel should be competent at rowing, oars should be of a suitable length (approximately 1.5 times the width between rowlocks), and secure rowlocks of the closed type are recommended. Inflatable dinghies are relatively safe with their built-in buoyancy. In the event of overturning, they can be righted by threading the bow rope around one rowlock, standing on the opposite side and pulling hard on the rope to overturn it again. Aluminium dinghies are light and durable. Their lightness makes them easy to row, but prone to being blown with the wind, which may make them unsuitable for windy conditions. If they become swamped, two people can remove most of the water by depressing the stern until the bow is well out of the water and then, quickly raising the stern, it can then be bailed out by a person alongside. When partly bailed out, boarding can be accomplished over the stern with a second person holding the bow down; then the remaining water can be bailed out. Wooden and fibreglass dinghies are often too heavy for this technique, but may float higher when swamped, thus allowing the use of a bailer.

8.6 SAFETY PRECAUTIONS WHEN WORKING WITH CABLEWAYS

Before using any cableway, personnel should check the condition, looking for signs of anchorage movement, changed sag, vandalism or other damage to the cable, backstays, anchorages, cable hardware and cable car. Manned cableways normally require regular inspections and the issuance of a fitness certificate. The certificate should be current. Personnel should never board the cable car without the on-site operator.

When using cable cars, whether moving or stopped, all personnel must be instructed never to touch the cable with the hands, because of the danger of being run over by the cable car wheels. The appropriate pulling device must be used instead. The maximum design load of the cableway must not be exceeded, and wire cutters should be carried to cut the suspension wire if it becomes entangled in the river. The wire should be cut close to the reel, and personnel should hold on tightly to the cable car during the rebound.

Unmanned cableways generally have powered or manual winches on the bank, and these need ratchets and brakes that lock firmly. As with the use of all winches, long hair and loose clothing must be fastened back to avoid being caught.

All cables and wires should be installed and used with due regard for the safety of river traffic and aircraft, particularly helicopters. Where appropriate, they must be marked with suitably durable and visible markers to indicate their presence to operators and pilots.

8.7 SAFETY PRECAUTIONS WHEN HANDLING EQUIPMENT

8.7.1 Surveying

Overhead electrical wires are a hazard when using survey staves, particularly metal ones. Signs warning of this hazard should be affixed to the back of staves, at eye level.

8.7.2 Chainsaws

Operators of chainsaws should wear suitable closely fitting clothing and safety equipment, including hard hat, ear protection, eye protection and strong work boots with steel toe-caps.

The saw should be started while being held on the ground. Cutting should be carried out in a position with firm footing, clear of obstructions and other people, and with a safe exit from falling timber or rolling branches.

Kickback can occur when the chain recoils upward from striking an obstacle. It can recoil far faster than a person's reaction time and may cause the operator to lose his or her grip. Lacerated left hands are common in this situation. In order to reduce the likelihood of this occurring, operators should maintain a firm grip with a straight wrist and good footing, cut at peak revolutions, and keep the nose of the bar away from obstructions.

8.7.3 Electrical equipment

All electrical equipment used outdoors or in damp conditions must be powered from an isolating transformer or an earth-leakage current-tripping device. All electrical leads should be routed to prevent damage from abrasion and contact with water. Leads must be kept in good repair, and any frayed or damaged connections should be properly repaired.

Circuits should not be overloaded, and repairs that should be done by a qualified electrician should not be attempted.

8.7.4 Power tools

Power tools should be used for their intended purposes only and always in accordance with the manufacturer's specifications. Personnel should be properly instructed in the use of these items. The use of some air- or power-operated tools may require authorization by government agencies. Safety goggles should always be used with all cutting, grinding or drilling equipment.

8.7.5 Protective clothing and safety equipment

Personnel must be supplied with all safety and protective items required for the working conditions and equipment being used.

8.7.6 Radioactive equipment

Some items, such as soil-moisture meters and geophysical instruments, incorporate radioactive sources. These instruments will be appropriately marked and must be handled and stored with special care in accordance with the relevant regulations. Radiation emitted by the source can be hazardous to health. The radioactive material will usually be sealed within a stainless steel pellet. As part of the equipment, this pellet will normally be surrounded by a material such as plastic, steel or lead, which absorbs radiation. It must be ensured that the source is within this absorber when the equipment is not in operation. The pellet must not be handled under any circumstance. If it needs to be moved, long-handled tongs or similar equipment must be used.

Keeping a good distance is normally adequate protection. With some sources, significant exposure only occurs closer than 10 cm. Others require considerably more than this. It is imperative that the personnel determine the type and other details of the radioactive source being used and that they acquaint themselves with the recommended procedures and instructions for that source. Where possible, employers should provide protective gear to those personnel operating equipment with radioactive devices.

All instructions, procedures and regulations must be rigorously followed, and the equipment should be handled with the utmost care at all times.

8.7.7 Safety aspects of groundwater monitoring

In all instances, permission must be sought from the owners of wells. Pumps and airlift equipment for sampling, testing or developing wells should be in accordance with safety procedures for those types of equipment. Safe practices around drilling rigs are essential, and manuals of drilling practice should be consulted.

Entry into large-diameter wells for sampling should be avoided because of the potential presence of gases, as described in 8.2.3. Safety harnesses should be worn when working above large-diameter wells.

8.7.8 Dust menace

Dust results from the inadequate cohesion of soil particles during a dry period. Dust can cause excessive wear and tear of equipment, especially on calibration marks on gauging instruments. Personnel must ensure that dust is completely removed from the packing boxes of these instruments before packing them away after use.

8.8 SAFETY PRECAUTIONS WHEN HANDLING CHEMICALS

All chemicals, such as those used for the preservation of water samples, cleaning fluids and tracers, must be stored and handled with care. Inhalation of vapours or direct contact with skin, eyes and clothing should be avoided. Any spills must be cleaned up immediately by dilution with large quantities of water, neutralization or mopping up of the chemical followed by disposal of the material. Gloves, aprons and suitable clean-up materials should be made available for this purpose.

No pipetting should be done orally, except when potable waters are the only substance being used. Skin that has been in contact with acids, bases or other corrosive substances should be washed immediately with plenty of water. A neutralizing solution may be applied if appropriate, to be followed by a second washing with soap. If any chemicals enter the eyes, they should be rinsed immediately with plenty of water. Rinsing around the eyes should be done as well. It may be necessary to hold the eyelids open during the washing procedure. Rinsing should continue for several minutes. All eye injuries must be treated professionally.

Precautions must be taken as water may contain a variety of toxic or bacterial hazardous substances. These may be derived from a wide range of sources, such as wastewater or effluent discharges, leachate from landfills, leakages from storage tanks, washing of agricultural spray tanks, and chemical or oil spills.

Any unusual appearance, colour, film, frothing, odours or vapours must be treated as suspicious and adequate precautions must be taken. Many toxic substances can enter the body through the skin and, in the case of vapours, through the lungs.

They can cause eye irritation, skin irritation, pruritus, rashes, nausea, stomach pain, decreased appetite, headaches, fatigue, coughing, wheezing and shortness of breath.

Precautions may include gloves, waterproof overalls, aprons, hats and eye protection. Where toxic vapours might be present, work should only be carried out in well-ventilated areas or with the use of self-contained breathing apparatus. Food should be kept away from samples and sampling locations. Personnel should always wash hands thoroughly before handling food. Smoking while sampling or near samples should be prohibited. If flammable compounds are expected to be present, personnel should keep sparks and heat sources away, store samples in special explosion-proof refrigerators and maintain the application temperature of the chemicals.

When measuring or sampling waters with high concentrations of toxic substances, such as leachate from landfills, or with suspected radioactivity, special considerations are required and the appropriate specialist should be consulted.

8.9 SPECIAL PRECAUTIONS FOR COLD CONDITIONS

8.9.1 Hypothermia (exposure)

Hypothermia is a condition of lowered body temperature caused by exposure to cold and results in rapidly progressing mental and physical collapse. Its onset is caused by cold temperatures aggravated by wet clothes, wind, hunger and exhaustion. It often occurs in conditions where its early symptoms may not be recognized.

Early symptoms of exposure may include signs of tiredness, cold and exhaustion, lack of interest, lethargy, clumsiness and stumbling, slurred speech and irrational behaviour. These signs constitute a medical emergency and require immediate action to prevent further heat loss and to effect rewarming. The victim may not complain and possibly deny that there is a problem. Later symptoms indicating a very serious emergency include obvious distress, a cessation of shivering despite the cold, collapse and unconsciousness.

Rewarming must be started immediately when symptoms become evident. The victim's body will probably be incapable of generating sufficient warmth to accomplish this, and warmth must be applied gradually to the torso, but not to the limbs and extremities. Warming the extremities will increase blood circulation to these cooler parts of the body and reduce the temperature of the body's core still further.

The requirements for rewarming are shelter, dry clothes, insulation (such as a sleeping bag), and warmth applied to the vital organs of the body. The latter can be done through close body contact, for example, by sharing a sleeping bag. The person should not be rubbed nor should direct heat be applied. Warm, sweet drinks, but never alcohol, are helpful to a person who is conscious.

With warmth and shelter, patients often appear to recover quickly, but a resumption of cold conditions can bring on collapse. Full recovery can take up to two days.

Hypothermia can be prevented by providing adequate shelter and insulated and windproof clothing. One should avoid prolonged wet conditions and have food and shelter available, such as a tent or bivouac. Employers and contractors can also provide warm-up shelters at the workplace where workers can find refuge from the cold and drink hot beverages. Warm, sweet drinks and soups are better than coffee, as coffee increases heat loss from the body.

When work involves riding on an open vehicle or some activity that generates wind, the number of stops should be increased appropriately.

8.9.2 Frostbite

Exposure to extreme cold causes freezing of the outer parts of exposed tissues, such as toes, ears, fingers and nose. Affected parts become numb, dull white in colour and waxy in appearance. Superficial frostbite can be treated by applying a hand or another part of the body to the affected area, without rubbing. Rewarming should not be done by direct heat or rubbing, or with alcohol. More serious frostbite requires medical treatment.

Prevention involves wearing adequate foot, hand, face and ear protection, avoiding tight-fitting clothing or boots, keeping hands and feet dry, and constantly monitoring for signs of numbness. Constant movement or wriggling of toes and fingers to stimulate circulation is a short-term remedy that should be followed to reduce the effect of exposure to cold.

8.9.3 Working on ice-cold lakes and streams

Travel and work on ice should be done with great caution, keeping weight to a minimum. If one falls through ice, outstretch arms onto solid ice, kick to keep the body level, crawl forward on the stomach until hips reach the ice, then make a quick full-length roll onto the ice. Keep rolling until safe. If the ice is too thin for support, one should make one's way to shore by breaking the ice with one hand while supporting oneself with the other.

Rescuers should try to reach the victim with a pole, board or rope. Going out to the ice edge should only be done as a last resort. If it becomes necessary, rescuers should carry a long pole or slide along in a prone position. If there is a rope available, it should be secured to an object on shore. A person who has fallen through ice must be dried and rewarmed as soon as possible to prevent hypothermia.

Considerable risk may be involved in taking measurements through ice. Drilling or breaking a hole may significantly reduce the strength of the ice. Ice in a stream is likely to be of variable thickness, and its strength cannot be estimated from its apparent thickness near the edge. Areas with rapids or flow disturbances, such as bridge piers, are likely to have thinner ice owing to the water movement. In advancing across an ice-covered stream, it is advisable to test the ice with an ice chisel every few steps. Hard ice will give a resounding ring, and soft ice will give a dull thud. A safety rope should be employed when there is any doubt, and a companion equipped with suitable rescue equipment should be on the bank.

8.9.4 Working in mountainous areas

The weather in mountainous areas can change rapidly, causing problems for the unwary or ill-equipped. The colder the climate, the greater the potential problems and the more clothing, supplies and safety equipment are required.

Personnel need to be experienced or be with someone who is, and the party's travel plans should be known to an appropriate person who could initiate assistance should this become necessary. Adequate waterproof, windproof and warm clothing should be worn and carried, as well as sufficient food and survival equipment for the weather extremes. Ensure that all persons arriving at the site by helicopter have this equipment with them even if they have been dropped off only for a short time, as cloud or other weather conditions may prevent the helicopter's return.

Venturing out on hard snow is not recommended without an ice axe, climbing rope and crampons, and knowledge of their use. It is important to be wary of avalanches, particularly just after snowfall or rain, to be aware of the various causes of unstable snow, and to seek advice from experienced persons. Whatever the snow conditions, travel on or below steep slopes should be avoided. If caught in an avalanche, one should make every effort to stay on top to avoid being buried, cover the nose and mouth to prevent suffocation and, if buried, try to make an air space in front of the face and chest.

8.9.5 Cold-water survival

Hypothermia will result very rapidly from immersion in cold water. Its onset can be delayed by remaining still and having sufficient coverage of clothing to reduce water movement against the body with its accompanying heat loss. It usually helps to keep as much of the body as possible out of the water, as the body loses heat much more quickly to water than to air of the same temperature.

It is preferable to keep the head above water and to draw the legs up in contact with the groin area to reduce heat loss. A life jacket is invaluable in assisting with this, and will also provide insulation to the core parts of the body. A number of people should huddle together, holding on to each other facing inwards with the sides of the chest pressed together to reduce heat loss. Children should be held in the centre of such a group.

Treatment involves rewarming of the vital organs of the body prior to warming the limbs and extremities, as described in 8.9.1.

8.10 SPECIAL PRECAUTIONS FOR HOT CONDITIONS

8.10.1 Heatstroke (hyperthermia)

Heatstroke is caused by exposure to high temperature that causes the body temperature to rise above 40°C. Adverse response to high heat varies among people depending on their acclimatization, level of fitness and, most importantly, body hydration. With the onset of excessive heat, the body loses heat primarily by the evaporation of water through sweating and respiration. If this loss of water is not replenished, the cooling mechanisms are inhibited and heat builds up. Symptoms include headache, chilling, nausea, rapid pulse, muscle pains, loss of coordination and, more severely, delirium and convulsions. If not treated, death follows.

Treatment involves immediate cooling by placing the victim in the shade, removing clothes and spraying with cold water while fanning vigorously. The victim is given fluids when fully conscious.

Precautions include being physically fit, moderating exercise, drinking moderate amounts regularly and often, avoiding alcohol and caffeine, avoiding working in the hottest part of the day, wearing lightweight, light-coloured, loose-weave clothing and a wide-brimmed hat, and adding extra salt to meals. Employers can also use some of the following measures if their workplaces are very hot:

(a) Engineering controls include using isolation, redesign or substitution to remove heat sources from work areas, air conditioning to cool the entire workplace, spot cooling for hot areas and worksites, local exhaust to remove heat from workplaces, automation of hot processes, as well as ensuring that the maintenance programme quickly fixes problems that create hot conditions such as steam leaks;
(b) Fans can increase the airflow and reduce humidity. Improving the airflow increases the cooling effect of sweating. However, if the air temperature is at or above body temperature, fans will simply expose the body to more hot air. This increases the heat load and the risk of heat stress disorders;
(c) Administrative and other measures for occasional hot indoor and outdoor work situations include providing regular rest breaks, providing adequate amounts of drinking water, proper salting of food, training workers to recognize and treat heat stress disorders, removing pregnant employees from hot work areas, scheduling work for cooler times of the day and providing light-coloured, lightweight and loose-fitting cotton clothing.

Note: Workers should be strongly encouraged to frequently drink small amounts of water or other cool (but not cold) fluids. One cup of fluid every 15–20 minutes can replace water lost in sweat. If workers drink only when they are thirsty, they may not get enough fluids.

8.10.2 Sunburn

Excessive exposure to the sun can cause severe sunburn, particularly to those with fair skin. It will cause severe pain, damage to the skin and possibly heatstroke. Prolonged exposure to the sun's ultraviolet rays can cause skin cancer, with fair-skinned people at the greatest risks.

Precautions include wearing protective clothing, with attention to head covering. Sunscreen lotions should be applied to the exposed skin. Exposure to the sun should be confined to short periods each day, with gradual increases to build tolerance.

8.11 TRAVEL AND TRANSPORT

8.11.1 General

Modes of travel and transport for hydrological work are many and varied in accordance with the wide range of terrain, climate and routes to be covered. Safety in terms of travel, taking into account all of the variations of these factors, is a wide topic in itself and is not confined only to hydrological work. Accordingly, it is only covered briefly here, and hydrologists are urged to seek out manuals and advice for particular local conditions and modes of travel.

8.11.2 Helicopters

On the ground, the noise, wind and urgency associated with helicopters tend to mask the dangers presented by the main and tail rotors. These have killed and maimed many people. One must not approach or leave the helicopter without the pilot's knowledge and approval, and this should be done within the pilot's field of vision. One should approach and leave the aircraft on the downslope side for maximum clearance from the main rotor. One should never walk around the tail.

Personnel should keep away from the landing pad or zone, and keep it clear of equipment. All equipment and loose articles should be kept well out of reach of the effects of rotor wash or they should be heavily weighted down. Long objects, such as survey staves, should be carried horizontally at waist level to avoid contact with rotors. The aircraft should be loaded under the supervision of the pilot, whose attention should be drawn to hazardous cargo, such as batteries and fuel.

Cableways and aerial wires are particularly hazardous to helicopter operations, and personnel should make the pilot aware of any that are known and assist in looking out for others.

8.11.3 Motor vehicles

In much hydrological work, frequent travel by motor vehicle means potential for serious accidents. Travel on remote, backcountry roads is common, and this provides additional hazards to those that can be encountered on highways.

The most common causes of accidents relate to excessive speed. This is no less true of backcountry roads, which are often narrow and winding and

Table I.8.1. Checklist for vehicle maintenance

Check outside every time the vehicle is driven to ensure that:	Tyres are not low, tread is not worn away, windshield wipers work and there is sufficient cleaning fluid in the reservoir, and there are no leaks under the vehicle. Mirrors, directional signals, headlights, tail lights and brake lights are clean and not broken.
Check inside every time the vehicle is driven to ensure that:	All doors are fully closed and locked, seat and head restraint are comfortably adjusted, and drivers and passengers are correctly belted; gauges work and accurately reflect engine conditions; the driver is mentally and physically ready to drive; mirrors, vents and windows are properly adjusted.
Check once a week	Oil level is sufficient before starting the vehicle. Washer fluid level is adequate.
Check once a month	Automatic transmission and brake fluid levels are satisfactory.
Check every six months	Windshield wiper blades, tyres and power steering fluid level are adequate.

have loose surfaces. The best drivers tend to accelerate smoothly, corner carefully and brake gently, being considerate of their vehicle, their passengers and other road users.

Keeping a vehicle in good working order helps to maintain control in adverse driving conditions. Table I.8.1 provides a checklist for vehicle maintenance.

8.12 SURVIVAL KITS AND RATIONS

Personnel in remote areas should carry emergency survival kits. The components of these kits will vary greatly depending on the climate, conditions and mode of travel, but should include long-life emergency food, water, water purification tablets or iodine, cooking and heating equipment, shelter, such as a tent or bivouac, sleeping bags, lighting, medical supplies, adequate clothing for the worst possible conditions, toiletry items and signalling equipment, such as a mirror, flares, walkie-talkies, mobile phones and two-way radio. A checklist for personal protective equipment is provided in Table I.8.2.

First-aid training should be given to all field personnel, and each person should be supplied with an adequate first-aid kit and manual. Topics to be covered should include rescue breathing, cardiopulmonary resuscitation, unconsciousness, bleeding, fractures, shock, eye injuries, poisoning and burns.

Personnel should check their emergency preparedness planning at least once every six months. This will enable them to update their survival kits.

Table I.8.2. Checklist for personal protective equipment[a]

Type	*Equipment*
Chemical and disease protection	Aprons Eye/face splash guards Gloves (vinyl and/or latex), sizes S, M, L and XL Protective suits, sizes S, M, L and XL Respirators (certification required for use)
Climatic and UV protection	Boots Fluids (for example, water and sports drinks) Hat, wide-brimmed Insect repellent (unscented) Rain gear Sunglasses Sunscreen Temperature-modifying clothing
Flotation and reflective protection	Orange flotation vest and jackets Safety harness
Protection for working around heavy objects and machinery	Black belt Hard hat Hearing protection Safety glasses Steel-toed safety boots Work gloves

[a] Personal protective equipment must be selected based on the hazard to be encountered.
Source: Modified after USGS original (http://water.usgs.gov/owq/FieldManual/Chap9/A9.11.html).

8.13 OTHER HAZARDS

Field personnel should be familiar with, and always be on the lookout for, other hazards posed by their working environment. These include poisonous plants, stinging or biting insects, dangerous animals, quicksand and electrical storms. Also, bodily contact with or ingestion of some waters may pose significant health risks. In some localities, there may be possibility of attack by other people, for example, those who may be engaged in illegal activities. Employers have a responsibility to ensure that their employees are never unknowingly exposed to any such risks.

In case of remote field activities, personnel should travel with at least one local person who is familiar with most of the routes, people and the security situation. Some effort should be devoted to informing local leaders about the activities to be carried out in their area. This will increase community participation and cooperation.

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CHAPTER 9

DATA PROCESSING AND QUALITY CONTROL

9.1 GENERAL

Quality assurance programmes, such as the ISO 9000 series (see ISO, 2000), have been adopted by many agencies, putting in place practices that aim to formalize and standardize procedures, from data collection, through processing, to extensive data checking. Quality assurance typically encompasses training, best practices, recording errors and malfunctions, corrective action, checking and other quality control, and independent audit of the entire operation. This chapter will cover quality control, considered here as the process of checking and validation of the data, but not the wider topic of quality assurance.

Following their capture on some medium, whether paper, punched-tape or electronic digital form, hydrological data are converted to a form suitable for archiving and retrieval. In addition, at various stages, data undergo a range of checks to determine their accuracy and correctness. As computer archiving has become a standard practice in most countries, the processing will involve the data being converted to the required format early in the process.

Data are collected and recorded in many ways, ranging from manual reading of simple gauges to a variety of automated data-collection, transmission and filing systems. With accelerating developments in technology, it is now more important than ever that data-processing and quality control systems be well-organized and understood by the people involved in collecting and using them.

By way of example, a flow chart of a relatively simple system is depicted in Figure I.9.1.

It is noted that quality assurance encourages the adoption of recognized best practices and advances in data validation. It is recommended that, subject to the availability of resources, Hydrological Services should consider the adoption of a quality management programme such as that described in ISO 9001. Once this has been achieved, organizations usually employ an accredited certification agency to provide independent verification and advice on developing the programme (Hudson and others, 1999).

9.2 PRINCIPLES, CONVENTIONS AND STANDARDS

As disciplines, hydrology and climatology have followed the "rules" of good science, in that data collection and its use should always use recognized good practices and be scientifically defensible by peer review. These principles require that a conservative attitude be taken towards altering data, making assumptions and accepting hypotheses about natural processes that one would quite possibly understand less about than one assumes.

9.2.1 Conservatism, evidence and guesswork

The hydrologist has a duty to be conservative in carrying out any correction of data. In 9.7.2, it is suggested to use strict criteria for altering or adding data values. This must always be done using assumptions based on evidence rather than any element of guesswork. Where an element of guesswork is involved, this should be left to the user to carry out, although all information that may be of use in this process should be available, normally by way of filed comments or by being filed separately in the database.

Another important convention is that any alteration made to data should be recorded in such a way that others can follow what has been done, and why. It should not be necessary to refer to the persons who made the alteration for an explanation. An audit trail should be available, such that with the documented procedures the process can be tracked through and checked. This traceability is also a requirement for a quality system.

9.2.2 Data accuracy standards and requirements

A Hydrological Service or equivalent recording agency should formulate data standards in terms of resolution and accuracy for each parameter. This process should be done in conjunction with international standards such as detailed in the *Guide to Climatological Practices* (WMO-No. 100), and with consideration of the present and, more importantly perhaps, the likely future needs of the data.

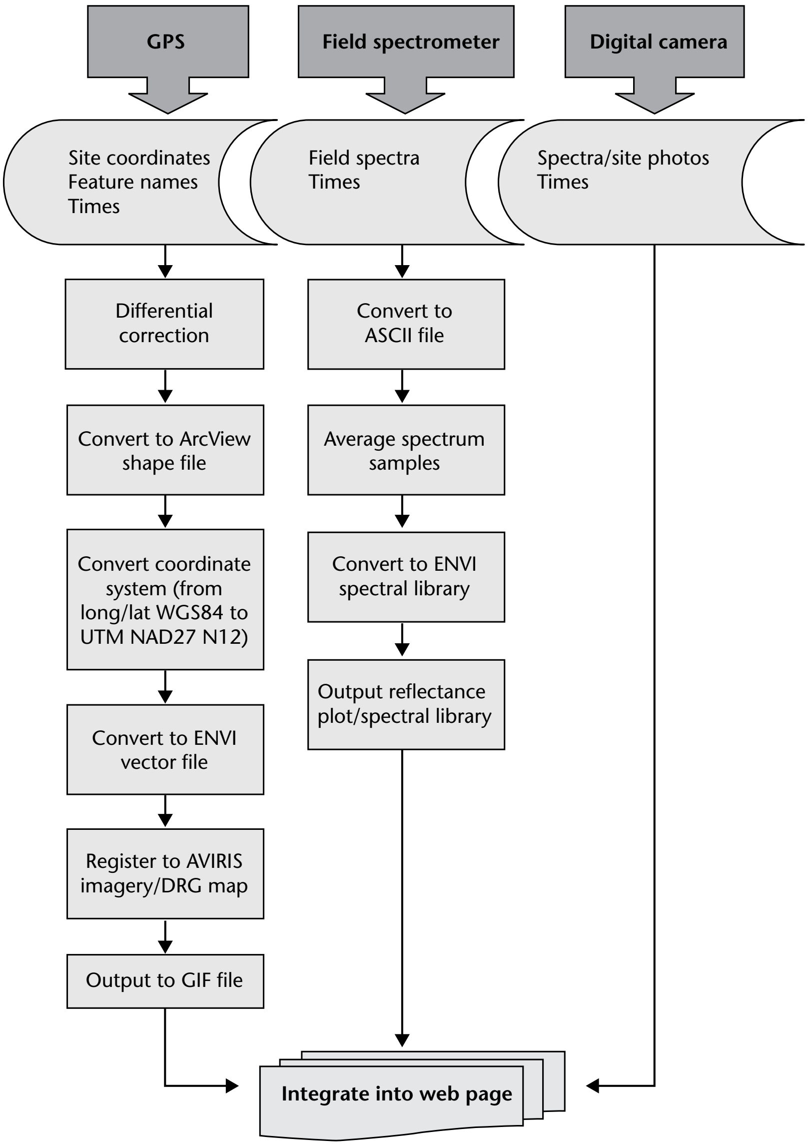


Figure I.9.1. Data-processing flow chart

When formulating data standards, it is important to distinguish between resolution, accuracy, errors and uncertainty:

(a) The resolution of a measuring device or technique is the smallest increment it can discern. For instance, a data logger and pressure transducer will often resolve a stage measurement to 1 mm, but the accuracy may be less than this due to errors resulting from drift or hysteresis in the transducer;

(b) The accuracy of a measurement relates to how well it expresses the true value. However, as the true value is often unknown, the accuracy of a hydrological measurement usually has to be expressed in terms of statistical probabilities. Accuracy is a qualitative term, although it is not unusual to see it used quantitatively. As such, it only has validity if used in an indicative sense; any serious estimate should be in terms of uncertainty (below);

(c) The error in a result is the difference between the measured value and the true value of the quantity measured. Errors can commonly be classified as systematic, random or spurious;

(d) Uncertainty is the range within which the true value of a measured quantity can be expected to lie, at a stated probability (or confidence level). The uncertainty and the confidence level are closely related; the wider the uncertainty, the greater the confidence that the true value is within the stated range. In hydrology, a commonly used confidence level is 95 per cent, which, in a normal distribution, relates to two standard deviations. For further information, see the *Guide to the Expression of Uncertainty in Measurement* (ISO/IEC, 1995).

The level of uncertainty that users of the data require is normally the prime consideration. Once this has been established, the uncertainties of the methods, techniques and instruments should be considered. Often there will be a compromise between the uncertainty desired and the accuracy and resolution of the instruments due to costs, practicalities and limitations of techniques.

The usefulness of data is, to a great degree, dependent on its completeness, and targets should also be set for reasonably expectable performance measures such as the percentage of missing records. It is recommended that agencies, rather than putting great effort into filling missing data with estimates, allocate resources (including training) to avoid the need for this.

9.3 CODING

9.3.1 General

A database will necessarily contain various code fields as well as the fields containing data values (also 2.3.2). This is because of the requirement for various descriptors to give meaning to the data, and these generally need to be codes so that the files are more compact and less ambiguous. A prime example is a code number for each recording station. Some codes, such as station number, will be a database key, but others will be codes that describe, among others, standard methods, data quality, measurement units and parameters. Depending on the database structure, codes may be required to signify what parameter a variable represents or, alternatively, this may be defined by the file format.

Coding systems should be comprehensive and flexible, and data collectors should be encouraged to make full use of the options available. In addition to the application of codes to guide the processing, comments should be included at this stage. These comments provide a general description of the data within defined time periods and should be available automatically when data are presented to users.

9.3.2 Developing codes

The steps involved in devising and using codes are:

(a) Define the data that require coding. These are normally descriptive data items that are used frequently, for example, the names of locations, variables, analysis methods, measurement units and data quality indicators;
(b) Decide when coding should be performed. To satisfy the objective of common recording and data-entry documents, coding should be performed at the time of data logging by the hydrological observer or the laboratory technician;
(c) Consider the adoption of existing (national or international) coding systems for some data items. Schedules of variable codes, laboratory analysis methods and measurement-unit codes have been developed by several countries. The adoption of such coding systems facilitates the interchange of data and reduces the need to devote resources to developing new coding lists;
(d) Consider possible current or future links to GIS (9.3.8) when compiling codes. For example, it could be beneficial to derive station and river numbering codes based on locations keyed to GIS;
(e) Obtain or prepare coding lists, incorporate the codes into the reporting and data-entry forms and the computer systems, and include coding instructions (and relevant coding lists) into technician instruction sheets;
(f) Train observers in the use of codes, monitoring completed forms very closely for the initial period after introducing or modifying the coding system. This should be done for several months to allow technicians to become familiar with the codes.

Most codes used for hydrological purposes are numeric. However, different combinations of alphabetic and numeric codes are also used. Alphabetic or alphanumeric codes are widely used for borehole logs and where more descriptive data are needed, such as soil land-use classification. The typical usage of codes in hydrological systems is described below and in the *NAQUADAT Dictionary of Parameter Codes* (Environment Canada, 1985).

9.3.3 Location codes

Codes normally exist for basin or sub-basin, and it is very useful to incorporate them into the station description data file (Chapter 2). This allows rapid identification of all stations (or stations measuring selected variables) in a single basin or group of basins. For additional information on station numbering, see 2.5.2.

9.3.4 Variable (parameter) codes

This heading covers the largest group of codes. The range of hydrological and related variables that may need to be included in a comprehensive database is enormous. Fortunately, several hydrological agencies have prepared and published variable-code lists (Environment Canada, 1985; United Kingdom Department of Environment, 1981).

The code lists normally comprise a four- or five-digit code for the variable, a text definition of the variable and possibly some abbreviations or synonyms. One feature that varies between the lists is whether the measurement units and/or analyses techniques (particularly for laboratory derived data) are included in the definition or are themselves coded. Thus, in one system variable code 08102 is dissolved oxygen measured in mg/l using a dissolved-oxygen meter, whereas another system describes the same variable as 0126 (dissolved oxygen) with measurement unit code 15, where 0126 and 15 are entries in the relevant code lists for mg/l and m, respectively.

9.3.5 Data qualification codes

With manual data collection it is common to have a set of codes available for the hydrological observer and the laboratory technician to qualify unusual or uncertain data so that future data usage may be weighted accordingly. There are basically two groups of qualifications – the first can be viewed as the current status (reliability) of the data value and the second indicates some background conditions that may cause a non-normal status. For both groups, the code used is normally a single alphabetic character, also known as a flag.

Flags for the status of the data are typically:

- E Estimated value, with an implication of a satisfactory estime;
- U Uncertain value, thought to be incorrect but no means to verify;
- G Value greater than calibration or measurement limit (value set to limit);
- L Value less than the detection limit (value set to limit);
- V Value outside normally accepted range but has been checked and verified.

Flags for background conditions may be:

- I Presence of ice (or ice damming);
- S Presence of snow;
- F Presence of frost;
- D Station submerged (during flood events);
- N Results from a non-standardized (quality controlled) laboratory;
- P Results from a partially quality controlled laboratory.

Flags should be entered if they are present and stored with the data to which they relate. The computer data validation procedures performed on the input data may generate more status flags, and the same codes may be used.

Alternatively, some database systems allow for the entry of plain-language comments into the database system (usually into a linked text file database).

9.3.6 Missing data codes

It is extremely important to differentiate between data that are missing and data that were recorded as having a zero value. If the data field for a missing numeric value is left blank, databases may automatically infill a (misleading) zero. Since a character value is not allowed in a numeric data field, this missing data problem cannot be overcome by inserting 'M' (for missing). One possibility is to enter the code *M* as a separate data-status flag, but in systems where flags are not used, some physically impossible data value, for example, –999, are entered in the data field to indicate a missing value to the processing system. If required, this value may be decoded to a blank or a "–" on output.

9.3.7 Transmission codes

Many systems for the transmission of data make use of some form of coding method, the purpose of which is to ensure that the information is transmitted quickly and reliably. This will require that data be converted to coded form before being transmitted or processed. Codes will need to be designed so that they are in a form compatible with both processing and transmission.

9.3.8 Geographical Information Systems

GIS are finding wide application in the fields of operational hydrology and water resources assessment. Their ability to assimilate and present data in a spatial context is ideal for many purposes, ranging from the provision of base maps to the operation of catchment or multicatchment models for runoff mapping and flood or drought forecasting.

In network planning and design, the ability to map quickly and display surface water and related stations enables a more effective integration to take place. Network maps, showing basins or stations selected according to record quality, watershed or operational characteristics, can be used for both short-term and long-term planning. The essential features of complex networks can be made very clear.

9.4 DATA CAPTURE

The term data capture is used to cover the processes of acquiring data from written, graphic, punched media, analogue or digital electronic form to a medium whereby these data can be further processed, stored and analysed. In recent years this medium has almost always been a computer, perhaps a mainframe, but usually a personal computer (PC) possibly connected to a network.

9.4.1 Key entry

Data collected as written notes, whether in notebooks or on forms designed for the purpose, will need to be entered into the computer manually. While some form of scanning with optical character recognition may be possible, it is usually preferable to avoid this unless the process is proven to be free of error.

Where observers are required to write data values on paper, it is recommended that they be issued with standardized forms (possibly in a book) that set out the required entries in a clear and logical sequence. Such forms can be produced on a computer word-processing package, and their issue and use should be controlled as part of the organization's data handling process. Examples of hydrometric data that may be written and later entered by hand include manual water-level readings, rainfall and other climate observations, and current meter streamflow measurements. There will also be secondary data entry in this category, such as short pieces of edited record and stage-discharge curves.

It is recommended that key entry of data be decentralized such that those persons responsible for data collection are also responsible for its entry and the initial data validation stages. Thus, data files will normally be produced on a PC, which will not need to be online or networked (except for the ease of data backup and transfer). As the size of the data files produced will be small relative to the capacity of memory or storage devices such as diskettes, data can be readily backed up and transferred for archiving according to the data handling and verification processes in place.

The minimum verification process for keyed data should be for a printout of the keyed data to be checked, entry by entry, with the original written record by a person other than the one who entered them. Checking will be enhanced if suitable graphs of the data can be made available. Even simple print-plots may be adequate. Where possible, and especially where there are large volumes of data to be entered, it can be useful to use automated data verification, such as range checks and previous and/or following value comparisons included in the data entry program.

9.4.2 Capturing chart data

Analogue records of parameters such as water level and rainfall were commonly collected in the past, and this technology still endures owing to the advantages of rapid interpretation, simplicity and the costs of changing instrumentation types.

Capture to computer records can be done by manual reading and keying, or digitizing from either a digitizing tablet or a scanner. Manual reading normally involves a person reading the series of values at an appropriate time interval, and transferring these to a form from which the values are later keyed into a computer file as described in 9.4.1.

Tablet or flat-bed digitizing is the most common method and relies to some extent on the skill of the operator not to introduce errors of precision into the record. The use of a scanner with software to interpret the trace is a more recent development, but is not widespread owing to the trend towards electronic data loggers.

Whatever the method, charts should be stamped with the prompts for date, time and water-level readings at chart off and chart on. As these indicate the adjustments to the original observations, the need for clear annotation is obvious. The most useful tool for verification of chart data is to produce a plot of the data once they are captured for comparison with the original plot. Preferably, these plots will be printed at the same scales as the original, so that the two can be overlaid (for example, on a light table) and any errors identified and subsequently remedied.

9.4.3 Punched-tape data

Electromechanical recording instruments were widely used from the 1960s to the 1980s, but have largely been replaced. These machines usually punched binary coded decimal (BCD) values at each time interval on to a roll of paper tape, and were the first commonly used machine-readable recorders. They could be read relatively rapidly by an optical tape reader and captured to computer file.

Data-processing operations were similar to those used for the later solid-state data logger, and verification processes developed for them are the basis of those used today for electronic data.

9.4.4 Electronic data logging

The use of electronic memory for storing values from sensors with various forms of electrical output has been common since the 1970s and became increasingly widespread during the last two decades of the twentieth century. As costs fall in at least real terms, these instruments have become more like computers and more easily connectable to them.

As data capture to electronic code is one of the data logger's primary functions, this step of data processing has become simpler. At the same time this technology has tended to make it easier for errors to be more serious and widespread so that quality control needs to be at least as rigorous as for other technology.

Unlike charts, forms and tapes, electronic data files do not exist in a tangible form to enable them to be easily identified, tracked and show evidence of how they have been modified. Batches of data, whether time series, point or sample data, need to be tracked and their processing managed through a register for each set of data. These registers, for reasons of simplicity, integrity and ease of use, are usually paper-based folders of forms. However, they may also take the form of electronic files, such as spreadsheet or database files, if these criteria can be satisfied.

9.5 PRIMARY PROCESSING ACTIVITIES

9.5.1 General

Primary processing is defined here as the processing steps required to prepare the data for storage in the repository or archive from which they will be available for use in the medium term and/or long term (Figure I.9.2). There will usually be some quality control and verification steps employed during this process; these are described separately in later sections.

Depending on the type of data, the primary processing stage may involve several steps and some labour, for example, with chart processing or simple file translation with little or no editing, such as for a precisely set-up data logger.

Data may also be used prior to this processing, for example, with telemetered water levels; however, users should be made aware that the data are unverified and may contain errors.

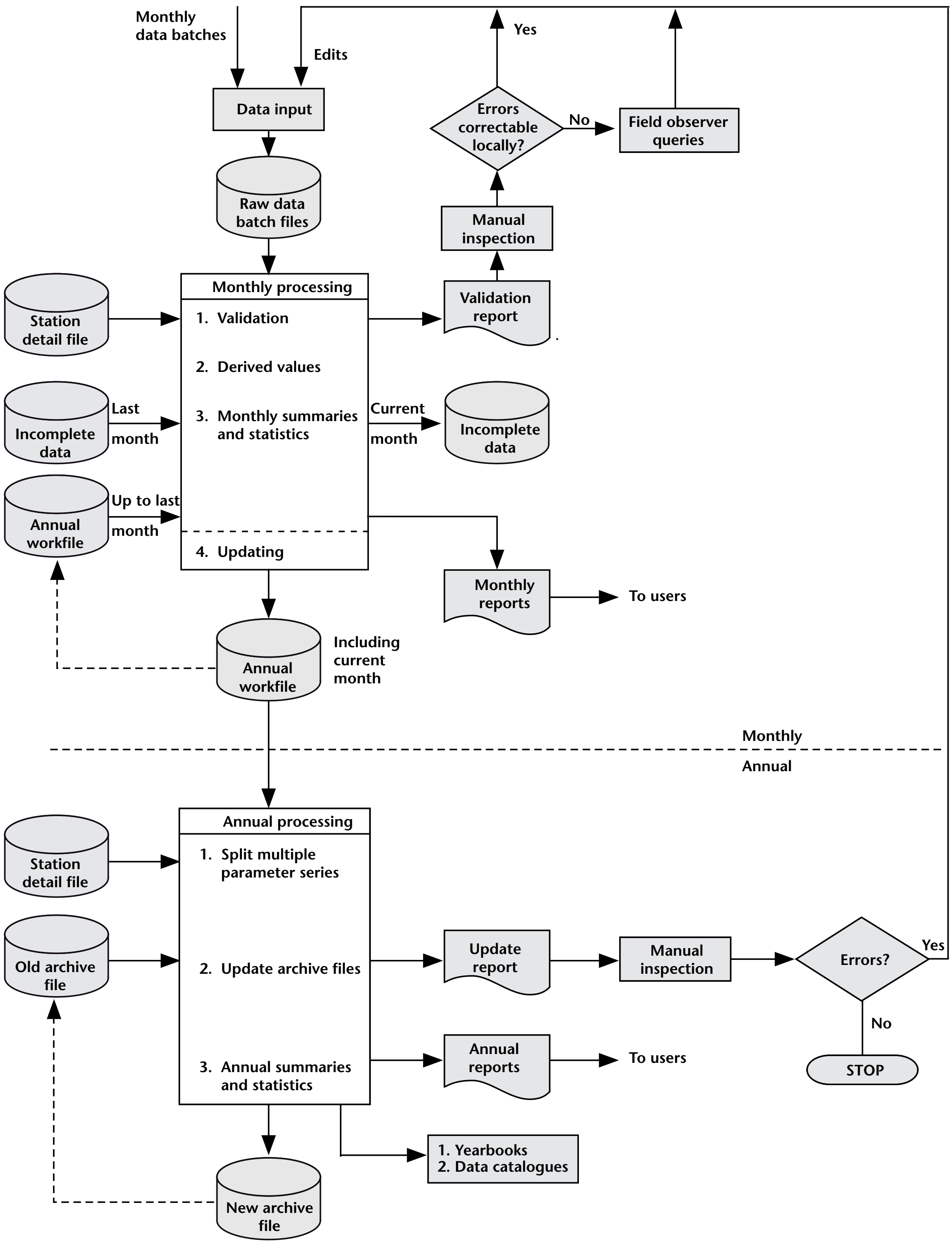
Secondary processing is regarded here as the steps necessary to produce data in a converted, summarized or reduced form, for example, daily rainfall from event data or daily mean discharges from stage and rating data. This is covered further in 9.7.

9.5.2 Preliminary checking of data

The difference between preliminary checking and error detection is rather arbitrary. Procedures included under preliminary checking in one country may be thought of as error detection in another. Also, the extent of the use of computers in processing the data may change the definition of preliminary checking. For instance, for data collected manually and later captured to computer files (perhaps by key entry or optical scanning), the term preliminary checking will be used to cover those procedures performed prior to transcribing the data into machine-readable form. For data collected directly to computer-readable files, there may be little prior checking other than verifying the proper identification of the batch and its associated manual readings (identification of site of collection, proper beginning and ending dates of this unit of data, and proper identification of the type of data involved, such as items sampled and frequency of sampling).

For data collected manually, preliminary checking should generally include the following steps:

(a) Log in data to a register at the time of the receipt of the report form;



Notes:

1. Monthly processing typically starts 10–15 days after month ending.
2. Annual processing run typically starts 30 days after year ending.
3. Archive files may be held totally offline (tape or diskette) or may be a mixture of online (for example, last two years online) and offline.
4. Small-scale data edits may be performed by online visual display units (VDU) or video terminals.
5. Validation and monthly reports shown separately may be the same document, particularly for parameters that do not need transformation, for example, rainfall.

Figure I.9.2. A two-stage processing/updating procedure for hydrological data

(b) Ensure completeness and correctness of the associated information, that is, dates, station name and station identification, if required in subsequent machine processing;
(c) Ensure completeness of the data;
(d) Check the observer's arithmetic, if any;
(e) Compare the observer's report with the recorded data.

In many countries, this last step will be taken following computer plots of the data.

Corrections on the forms should be entered legibly and in ink of a different colour from that used in the completion of the original form, making sure that the original entry is not erased or made illegible. It is usually best if these corrections are also dated and signed by the person carrying them out.

Certain preliminary checks should also be applied to data from chart recorders. The times recorded at the beginning and end of the chart, and at any time check in-between, should be checked against the timescale on the chart to determine if time corrections need to be applied, or to determine the magnitude of the time correction. An attempt should be made to determine whether a time correction is due to clock stoppage or whether it can reasonably be spread over the chart period. All manual readings should be written on the chart in a standard format.

For data-logger data, preliminary checks on time and comparison with manual readings will normally be part of the field data capture routine. Depending on the software available, checks may also include plotting the data on screen before leaving the station to confirm that all is operating correctly. Where this is possible, it should be included as part of standard procedures.

Upon return to the office, preliminary checks will include registering the data and the associated information, and appropriate backups of the files in at least three independent places (for example, PC hard drive, portable disk and network drive).

For telemetered digital data, there may be little or no preliminary checking before they are handed over to a user. In such situations, the user should be made well aware of the unverified condition of the data and use them accordingly. Even when there is an automated checking process in operation, it will only be able to check certain aspects of the data (for example, range, spikes, steps or missing values) and the user should be made aware of the limitations.

Usually, and this is recommended procedure, telemetered data will also be filed at the station or another secure part of the system and will only be updated to the archive and/or verified status after full preliminary checks (as for data-logger capture above) plus error detection and validation. Quality codes, if used, may assist with communicating these issues to users.

9.5.3 Traceability and processing

Hydrological data are valuable in that they are relatively expensive to collect and irreplaceable, and potentially have very high value following certain events. To realize and maintain their value, a means of verifying the accuracies and giving assurance that errors are largely absent must exist. Thus the traceability of the data and the methods used to collect and process them must be available in a readily followed form. Hydrological agencies should establish procedures aimed at achieving this traceability, in conjunction with the efficient processing of the data while preserving and verifying their integrity.

A data-processing system should include provisions for:
(a) Registering the data after collection to confirm their existence and tracking their processing;
(b) Keeping backups of the data in original form;
(c) Positively identifying the individual batches of data at the various stages of processing;
(d) Identifying the status of data as to their origin and whether they have been verified as fit for use;
(e) Presenting and storing evidence of any modifications to the data;
(f) Filing all field observations, log books, forms, etc., which verify the data;
(g) Controlling the amount and type of editing which can be performed and providing the authorization to do so;
(h) Presenting the data in a number of ways for checking and auditing by trained persons who are to some extent independent of the process.

9.5.4 Data registers and tracking

As soon as data reach the field office (whether by telemetry, as computer files, charts or on handwritten forms), they should be entered into one of a set of registers, usually classified by to station and data type, and in chronological order.

These registers are usually on hard copy in a folder (but may be electronic) in the hydrological office and are updated daily as batches of data arrive.

Initially this involves noting the starting and ending times of the data batch, and continues with confirmation of editing, checking and updating the database. Each step should be signed with the staff member's initials and date, in order that staff take responsibility for, and gain ownership of, their work and its progress. The registers will thus contain a verified chronological record of data-processing activities in the field office.

9.5.5 Identification and retention of original records

All data are to be permanently identified with the station numbers and other required codes. Charts require a stamp or label to prompt for the dates and times, manual readings, etc., for both chart on and chart off. Forms, cards and other hard copy should be designed with fields that prompt staff for the required information.

This material should be archived indefinitely in suitably dry and secure storage, with an adequately maintained indexing system to enable retrieval of specific items when required. Some safeguards will be required to prevent undue deterioration, for instance against mould, insects, vermin or birds. Some media may gradually become unreadable for other reasons; for instance, foil-backed punched-tape will bind to itself if tightly wound, and will also become difficult to read as the tape readers and their software become obsolete and unable to be run. In such instances it may be advisable to use imaging capabilities to store this information in an electronic format. Such a decision will need to be based on a cost–benefit analysis.

Electronic data should have an adequate file-naming system and an archive of the unaltered original data files. It is permissible, and normally advisable, for these files to be transformed into a durable computer-readable format that will include the station and other identifiers, and in future not depend upon software or media that may become obsolete. It is recommended that data-processing and database managers pay attention to this issue when developing and updating their systems.

It is recommended that an original record of electronic data be retained on hard copy in the form of a suitably large-scale plot or perhaps a printout of the values if the data set is small. This is filed initially in the processing office, both as a backup of the data and as the record of processing if all transformations, modifications and other steps are written on it, and signed and dated by the processor. Other documents, such as plots following modifications, should be attached, and if adequate comments are added, this can become a simple but complete record of the processing. Some of the more advanced software packages may include provisions to compile such a record electronically, and some offices can configure proprietary database software to do this; however paper-based systems are generally simpler, arguably more foolproof and easier to understand and use.

9.5.6 Data adjustments for known errors

These are the errors reported by the field technician or those persons responsible for manual quality control of the incoming data sets. Corrections for these errors must be made before the data are submitted for validation. The errors may be associated with a gradual drift of the clock, sensor device or recording mechanism, but may also be caused by discrete events, for example, clock stoppage or electronic fault. In the former case, a time-series database may automatically perform the required adjustment using linear or more complex scaling of recorded values. In the latter case, it may be possible for manual estimates of missing data to be inserted under certain conditions (9.4 above), if the affected period is not too long and sufficient background information is available.

Adjustments may also be required to compensate for more complex phenomena, such as the presence of ice at river-gauging stations. In this case, it is almost certain that the corrected stage values would be manually computed for the affected period. Again, this needs to be strictly controlled as to which assumptions are permissible. Reporting of errors should use standard procedures and standard forms. The form may be used for noting corrections to stage or flow. An essential feature of the correction process, whether performed manually or by computer, is that all modified data should be suitably flagged and/or comments filed to indicate all adjustments that have been made.

Where adjustments are to be made to either time or parameter values in each batch, the following points must be answered before proceeding:

(a) Are there valid reasons for the adjustments?
(b) Are the adjustments consistent with the previous batch of data?
(c) Is any follow-up fieldwork necessary, and have the field staff or observers been notified?

Answers to (a) and (b) must be fully documented in the processing record.

9.5.7 Aggregation and interpolation of data

Many variables, because of their dynamic nature, must be sampled at relatively short periods, but are only utilized as averages or totals over longer periods. Thus, for many hydrological applications, climatological variables may be required only as daily values, but must be sampled with greater frequency to obtain reliable daily estimates. Temperature and wind speed are good examples, but the same can be true for water-level and river-flow data. In the past, when computer storage costs were more significant, the levels of data aggregation were sometimes different for data output and data storage purposes. Modern time-series databases, however, will generally have efficient storage and retrieval capabilities that will enable the archiving of all data points. Data at a high level of aggregation, for example, monthly and annual averages, will be used for reporting and publications or kept as processed data files for general reference purposes.

9.5.8 Computation of derived variables

Derived variables are those parameters that are not directly measured but need to be computed from other measurements. The most common examples are runoff and potential evapotranspiration. However, the full range of derived variables is very broad and includes many water quality indices.

One important database management decision is to determine whether derived variables need to be stored after they have been estimated and reported. It is obviously not essential to occupy limited storage space with data that may readily be recomputed from the basic data held. For example, it is not usual to store sediment and dissolved salt loads, because these are used less frequently and may be very rapidly computed by the multiplication of two basic time series, flow and concentration.

Two differing examples illustrate this; in the United States, the Water Data Storage and Retrieval (WATSTORE) system (Hutchinson, 1975; Kilpatrick, 1981) keeps online daily average flows, while in New Zealand, the Time Dependent Data (TIDEDA) system (Thompson and Wrigley, 1976) stores only stages in the original time series and computes flows and other derived variables on demand. The only fixed rule is that whatever subsequent values are derived, the original data series should be preserved, in an offline, stable, long-term storage facility.

Most modern time-series databases will generally have capabilities such that recomputation is not an issue. With the deployment of data loggers featuring significant onboard programming and processing capability, a more significant issue is whether such variables should be computed by the data logger prior to primary data processing. It is recommended that they not be computed, in order to control and achieve standardization of methods; it is far easier to verify the methodology in a data-processing system rather than within the programs of a number of instruments that will inevitably become disparate over time and location.

9.5.9 Data status

The status of the data must be carefully monitored to determine whether they require validation or editing, or are in their final form and ready for use. Some database systems add a code to signify this; others provide a means of restricting access for manipulation and editing according to status level. For example, the United States Geological Survey's Automated Data Processing System (ADAPS) has three status levels: working, in-review and approved. Database systems without these facilities will require operating rules specifying which particular members of staff can have access to the various working and archive directories, and other privileges such as the write protection on files. It is recommended that, where possible, only one person operate this type of system for any one database. An alternative person, preferably at a senior level, should also have privileges in order to act as a backup, but only when essential.

9.6 SPECIFIC PRIMARY PROCESSING PROCEDURES

The above general procedures may be applied to various hydrological data types to differing degrees, and it is necessary to identify some of the specific procedures commonly practised. Several WMO and FAO publications (for instance, WMO-No. 634) deal directly with many of the procedures described below, and reference to the relevant publications will be made frequently. These texts should be consulted for background theory and the formulation of techniques, primarily for manual processing. This section presents some additional information required to extend such techniques.

9.6.1 **Climatological data** [HOMS H25]

For hydrological applications, apart from precipitation, the most significant climatological variables are temperature, evaporation and evapotranspiration, in the order of progressive levels of processing complexity. Before reviewing the processing tasks, it is useful to consider the means by which most climatological data are observed and recorded, because this has a significant impact on subsequent operations. The wide range of climatological variables and their dynamic nature have resulted in the situation whereby the majority of the primary data are obtained from one of two sources – permanently occupied climate stations and packaged automatic climate (or weather) stations. The implication of the first source is that the observers tend to be well trained and perform many of the basic data-processing tasks on site. Since the processing required for most parameters is quite simple, field processing may constitute all that is required. Even where more complex parameters need to be derived, observers are usually trained to evaluate them by using specially constructed monograms, or possibly computers or electronic logging and data transfer devices. Thus, computer-related primary processing, if performed at all, largely comprises the verification of the manual calculations.

The implication of the use of automatic climatological stations is that there exists a manufacturer-supplied hardware and software system capable of performing some of the data processing. Indeed, many climatological stations are designed specifically to provide evaporation and, normally, Penman-based, evapotranspiration estimates (Chapter 4). However, it should be carefully considered whether such variables should be computed by the data logger prior to primary data processing. This is not recommended in order to control and achieve standardization of methods. If variables do need to be computed, for instance where these data are used in near-real-time, it is preferable if the raw data are also entered into the database for computation using a more controlled and standardized method. Care must be exercised in the use of automatic climate-station data because the range of quality of sensors is highly variable by comparison with most manual climate stations. Further details on the processing of climatological data can be found in the *Guide to Climatological Practices* (WMO-No. 100).

There are several climatological variables that need to be transformed to standard conditions for storage and/or application. For example, wind speeds measured at non-standard heights may need to be transformed to a standard 2- or 10-m height by using the wind speed power law. Similarly, pressure measurements may be corrected to correspond to a mean sea-level value, if the transformation was not performed prior to data entry.

9.6.1.1 **Evaporation and evapotranspiration observations** [HOMS I45, I50]

Where direct measurement techniques are used, the computer may be used to verify evaporation estimates by checking the water levels (or lysimeter weights), and the water additions and subtractions.

To compute lake evaporation from pan data, the relevant pan coefficient needs to be applied. In some cases, the coefficient is not a fixed value, but must be computed by an algorithm involving other climatological parameters, for example, wind speed, water and air temperature, and vapour pressure. These parameters may be represented by some long-term average values or by values concurrent with the period for which pan data are being analysed. Pan coefficients, or their algorithms, must be provided in the station description file (Chapter 2). If an algorithm uses long-term average values, these too must be stored in the same file.

Details on the estimation of evaporation and evapotranspiration are discussed in Chapters 2 and 4. Existing computer programs for solving the Penman equation are provided in HOMS component I50.

9.6.1.2 **Precipitation data** [HOMS H26]

Data from recording precipitation gauges are frequently analysed to extract information relating to storm characteristics, whereas data from totalizing (or storage) gauges serve primarily to quantify the availability and variation of water resources.

Before analysing any data from recording gauges, it is necessary to produce regular interval time series from the irregular series in which the data are usually recorded. If the data have been subjected to a previous stage of validation, this time-series format conversion may already have taken place. The computer program used for conversion should allow the evaluation of any constant interval time series compatible with the resolution of the input data. The selection of a suitable time interval is discussed below.

Whether the data are derived from recording or totalizing gauges, first priorities are the apportionment of accumulated rainfall totals and the interpolation of missing records. Accumulated rainfall totals are common in daily precipitation records when, for example, over a weekend, a gauge was not read. However, they are also common with tipping-bucket gauges that report by basic systems of telemetry. If reports of bucket tips are not received during a rainfall period, the first report received after the gap will contain the accumulated number of bucket tips. The difference between this accumulation and that provided by the last report must be apportioned in an appropriate manner. The techniques for apportioning accumulated totals and estimating completely missing values are essentially the same. Apportioned or estimated precipitation values should be suitably flagged by the process that performs these tasks. Exactly the same techniques may be applied to shorter interval data from recording gauges; however, estimates of lower quality will be obtained because there will usually be fewer adjacent stations and because of the dynamic nature of short-term rainfall events. Precipitation may also be measured using different instruments and at non-standard heights. Therefore, data may need to be transformed to a standard gauge type and height for consistency. Further details on the processing of climatological data can be found in the *Guide to Climatological Practices* (WMO-No. 100), and in Chapter 3.

9.6.2 **Streamflow data**
[HOMS H70, H71, H73, H76, H79]

There are several processing steps required to produce streamflow data. The first deals with the water-level series data, the second covers the flow measurements, the third incorporates the gauged flows into rating curves and the fourth involves the final step of applying the rating curves to the series data in order to compute flows. Comprehensive details of techniques for flow computation are presented in the *Manual on Stream Gauging* (WMO-No. 519), but several time-series databases do this as a standard process.

9.6.2.1 Water-level series data

As for other series data, water-level series data should first be verified that the start date, time and values for the batch match up with the end values for the previous batch. It is useful if the initial processing provides the maximum and minimum gauge heights to enable an initial range check. Any unusually high or low values should be flagged to check that the values are in context.

The batch should be plotted to a suitable scale and examined to detect such problems as the following:

(a) Blocked intake pipes or stilling wells, which will tend to show up as rounded-off peaks and recessions that are unusually flat;
(b) Spikes or small numbers of values which are obviously out of context and incorrect due to an unnaturally large change in value between adjacent data points. Such situations can occur, for instance, with errors in the digital values between a sensor and a data logger input port;
(c) Gaps in the data, for which there should be known explanations, and a note as to the remedial action taken;
(d) Errors induced by the field staff, such as pumping water into a well to flush it;
(e) Restrictions to the movement of the float/counterweight system or the encoder (perhaps caused by a cable of incorrect length);
(f) Vandalism or interference by people or animals;
(g) Debris caught in the control structure, or other damming or backwater condition.

Note that such problems, if not detected during the field visit, must be investigated at the earliest opportunity. In cases where the cause has not been positively identified, full processing of the data should be delayed until it can be investigated on site.

Following examination of the plot, a description of the problems identified should form part of the processing record together with any printout showing data adjustments, editing and any other work. As well as any comments, the following should also be included:

(a) The date the data was plotted;
(b) The signature of the processor;
(c) Notes of all corrections to the data, plus any subsequent actions carried out, which change the data in the file from that which is plotted (for example, removal of spikes or insertion of manual data resulting from silting). Normally, if any corrections are applied, another plot is added to show their effects, and all evidence is filed.

Charts should be stamped with the prompts for date, time and water-level readings at chart off and chart on. As these indicate the adjustments to the original observations, the need for clear annotation is obvious.

9.6.2.2 Flow measurements

The computation of flows from current-meter gauging data is normally done in the field office or in the field depending on the instrumentation. Other methods, such as volumetric, dilution or acoustic moving-boat methods, will have a variety of computation methods that will also normally be performed in the field or field office. Further processing will include a computation check and possibly some post-processing if any adjustments are found necessary, for example to instrument calibrations, offsets, or edge estimates.

Primary processing will also include recording in the gauge register, and plotting on the rating curve, if applicable, and entry of the results into the database. Depending on the method and associated software, it may also include filing of the complete raw data file in the appropriate part of the hydrological database.

Owing to their influence on subsequent flow estimates, it is recommended that flow measurement data be submitted to suitable verification. This should include the calculation of statistical uncertainty using recognized methods, for example, in ISO 748 (ISO, 1995). If available from the techniques and software used, the process of verification should also include an examination of plots of the cross-section as well as of the velocities measured to check for gross errors and inconsistencies. If warranted by experience, provision should also be made to perform corrections for excessive deflection of sounding lines for suspended meters, and cases where velocities are not perpendicular to the gauged section (*Manual on Stream Gauging* (WMO-No. 519)).

9.6.2.3 Rating curves

Rating curves define the relationship between stage and flow. This relationship is determined by performing many river gaugings over a wide range of flows and by using the stage and discharge values to define a continuous rating curve. While control structures may have standard, theoretical ratings, it is a recommended practice to rate structures in the field.

Traditionally, rating curves have been manually fitted to the plotted measurements. In many cases the curve may be fitted more objectively by computer methods. If necessary, weights may be assigned to each discharge measurement to reflect the subjective or statistical confidence associated with it. However, because some sections have several hydraulic control points, many hydrologists prefer to keep the definition of rating curves as a manual procedure. Many factors have an impact on the quality of the rating curve. It is thus imperative that a flow-processing system be able to identify and locate the correct rating curve and be aware of its limits of applicability. Of particular note is the importance placed on preserving historic rating curves to allow flows to be recomputed.

There are two forms in which rating curves may be stored in the computer: functional and tabular. The tabular form is still the most common, and the table is prepared by manually extracting points lying on the rating curve. The extraction is performed so that intermediate points may be interpolated, on a linear or exponential basis, without significant error in flow estimation. The functional form of the rating curve has one of three origins:

(a) A theoretical (or modified) equation for a gauging structure;
(b) A function fitted by the computer to the gauged points, that is, automation of the manual curve-fitting process;
(c) A function fitted to the points of the table prepared as described in the previous paragraph, that is, a smoothing of the manually-fitted curve. A time-series database with hydrological functions will normally use this method.

9.6.2.4 Flow computation

Modern time-series database software will include a standard process to apply flow ratings to water-level series. Whether minor changes of bed level are applied as new ratings, or as shifts that apply a correction or offset to the water-level data, will depend on the capability of the software.

For either method, the rating to be applied must cover the range of water levels for the period, and if necessary should have been extrapolated by a recognized and defensible method and be valid for the period. Stage values should have been validated following any required corrections for datum, sensor offset and timing error. Where rating curves are related to frequently changing artificial controls, for example, gates and sluices, a time series of control settings may be needed to guide computer selection of the relevant rating curve.

Although the compilation of rating curves is simple in theory and is a standardized procedure, there is often some interpretation and decision-making required. This is due to the likelihood that the number and timing of flow gaugings will be inadequate because of practical difficulties in getting this work done. It is possible that the knowledge and experience of the hydrologist will be necessary to cope with such questions as:

(a) Which flood among those that occurred between two successive gaugings has caused a rating change or shift?

(b) Over what period of, for instance, a flood, should a progressive change from one rating to another be applied?
(c) Should a high flow gauging carried out in bad conditions or using a less accurate technique be given less weight when it plots further from the curve than the velocity-area extension predicts?

These and similar questions can lead to rating curves being subject to considerable scrutiny and sometimes revision following the completion of additional flow gaugings, especially at high flows.

A problem frequently encountered when applying multiple rating curves is that they can produce abrupt changes in flow rates at the time of change-over. If the processing system does not have the capability to merge ratings over time, then some means of manual adjustment of flows during the transition period will be required. If the stage values are being altered instead of the rating curve (not recommended), then these shifts can be varied over the time period to achieve this.

Shifting the stage values instead of producing a new rating is not recommended because:
(a) With original data being given a correction that is in fact false, considerable care and resources need to be applied to ensure that the correct data are safeguarded, and that the shifted data are not used inappropriately;
(b) The processes of determining, applying and checking shifts add considerable complexity to methods;
(c) Quality control processes (such as plotting gauging stages on the stage hydrograph or plotting gauging deviations from the rating) become more difficult to implement and use.

With modern hydrometric software, the effort required to compile and apply new rating curves is much reduced, thus avoiding the need to alter stage data as a "work-around".

9.6.3 **Water-quality data**

There are four main areas of activity in the primary processing of water quality data:
(a) Verification of laboratory values;
(b) Conversion of measurement units and adjustment of values to standard reference scales;
(c) Computation of water quality indices;
(d) Mass–balance calculations.

Verification of laboratory results may comprise the re-evaluation of manually-computed values and/or consistency checks between different constituent values. These operations are essentially an extension of data validation techniques.

The standardization of units is important in obtaining consistency of values stored in the database. The operations necessary comprise the conversion of measurement units used, such as normality to equivalence units, or correction of values to match a reference standard, for example, dissolved oxygen and conductivity values transformed to corresponding values at a standard water temperature of 20°C.

Water quality indices are generally based on empirical relationships that attempt to classify relevant characteristics of water quality for a specific purpose. Thus, indices exist for suitability, such as drinking, treatability, toxicity or hardness. Since these indices are derived from the basic set of water quality data, it is not generally necessary to store them after they have been reported. They may be recomputed as required.

Some indices have direct significance for water management. For example, empirical relationships of key effluent variables may be used as the basis of a payment scheme for waste-water treatment – the higher the index, the higher the charges.

Mass-balance calculations are performed to monitor pollution loadings and as a further check on the reliability of water quality data. Loadings are calculated as the product of concentration and flow (or volume for impounded water bodies). By computing loadings at several points in a river system, it is possible to detect significant pollution sources that may otherwise have been disguised by variations in flow. Obviously, mass-balance calculations must be performed after flows have been computed. Mass–balance calculations may be performed easily for conservative water quality constituents, that is, those that do not change or that change very slowly with time.

Non-conservative constituents, for example, dissolved oxygen and BOD, may change extremely rapidly and quite sophisticated modelling techniques are required to monitor their behaviour. Additional information and techniques can be found in the *Manual on Water Quality Monitoring: Planning and Implementation of Sampling and Field Testing* (WMO-No. 680) and the *Global Environment Monitoring System (GEMS) Water Operational Guide* (UNEP/WHO/UNESCO/WMO, 1992).

9.7 SECONDARY PROCESSING

Secondary processing is regarded here as the steps necessary to produce data in a converted, summarized or reduced form, for example, daily rainfall from event data or daily mean discharges from stage and rating data. It also covers the secondary editing following more complex validation, and the insertion of synthetic data into gaps in the record.

In addition, the regrouping of data and additional levels of data coding may be performed and measurement units may be converted to the standards adopted in the database. The conversion of irregular to regular time series is also one of the operations necessary in many cases. There are many options regarding the way in which data may be compressed for efficiency of storage, but modern database software and hardware are reducing the need for compression.

9.7.1 Routine post-computation tasks

A significant task for all data processing particularly relevant to flow data is that of performing the necessary housekeeping operations on data sets. These operations implement decisions on which data sets should be retained, and discard any data sets that are superfluous or incorrect and could possibly be mistaken for the correct data set. It is advisable to save only the essential basic data (and security copies) and, possibly, depending on the database software capabilities, any derived data that are very time-consuming to create. For example, in some systems, daily mean flows are time-consuming to derive and thus these data sets are retained as prime data. On the other hand, some agencies use software (packages such as TIDEDA of New Zealand and Time Studio of Australia) that compute these data sets rapidly from the archived stage and rating data, and thus there is no point in storing them beyond the immediate use. (It is inadvisable to do so, because these systems make it easy to update ratings when additional data become available, and thus the most up-to-date flow data will automatically be available.) (Details on the HOMS component, TIDEDA, are available on the WMO website at http://www.wmo.int/pages/prog/hwrp/homs/Components/English/g0621.htm).

Depending on the systems used, and for guidance purposes, the following flow-related data should usually be preserved:

(a) The stage data in their original unmodified form (data-logger files should appear where station and date/time information are embedded or attached);
(b) Field data relating to time and stage correction, and the corrections that have been applied in primary processing, along with the name of the person who made the corrections and dates;
(c) The adjusted stage data, that is, the time series of water levels corrected for datum, gauge height and time errors. A working copy and at least one security copy should be held (offline);
(d) The gaugings in their original form, whether written cards or computer files such as ADCP data;
(e) Rating curves, also in their original form, whether paper graphs or graphical editor files;
(f) Any associated shift corrections;
(g) If relevant daily average flows;
(h) Basin water-use data used to obtain naturalized flows, if these are calculated.

Generally, most other data sets will be transient or may be readily derived from these basic data sets.

It is vital that all electronic data sets be backed up offline and offsite. It is advisable to keep multiple backups at different frequencies of rewrite, with that of longer frequency stored in a different town or city. Original paper records should be kept in designated fire-rated and flood/waterproof purpose-built rooms, with access strictly controlled, or alternatively, if cost-effective, imaged and stored electronically.

9.7.2 Inserting estimates of missing data

The usefulness of data is, to a great degree, dependent on its completeness. However, filling missing data with estimates can severely compromise its value for certain purposes, and as future purposes may not be apparent when the data are collected or processed, this should be done with great caution and restraint. It should also be traceable, so that the presence of filled-in data is apparent to the user and the process can be reversed if required.

As mentioned in 9.2, the hydrologist has a duty to be conservative in carrying out any correction of data. An agency should formulate strict criteria for altering or adding data values, and this work must always be done using assumptions based on evidence rather than any element of guesswork.

The following are some suggested criteria relating to water-level and rainfall data as used for the national Water Resources Archive in New Zealand

(National Institute of Water and Atmospheric Research, 1999, unpublished manual):

(a) No alterations shall be made unless justification for the assumptions made is scientifically defensible, and recorded, as below;
(b) Such alterations must have the explanation recorded in the processing record, which may be a plot of the original data in the station's register or as a comment on the database;
(c) As a general guideline, gaps due to missing records will not be filled with synthetic data or interpolated. Any approximate data shall be made available to users by inclusion or reference to them in a comment in the database. Exceptions to the non-use of synthetic data and interpolation are in (d) to (e) below;
(d) A gap in a water-level record may be filled with a straight line or curve as applicable, if *all* of the following conditions are fulfilled:
    (i) The river is in a natural recession with the water-level lower (or the same) at the end of the period;
    (ii) It has been ascertained that no significant rain fell in the catchment during the time of concentration that would relate to the gap period;
    (iii) The catchment is known to be free of abstractions and discharges that modify the natural flow regime, for example, power station and irrigation scheme;
    (iv) The resulting plot of the data shows consistency with the data on either side;
    (v) In some situations (for example, power stations), an adjacent station may measure the same data or almost the same data. In the former case, the record can be filled in as if it were a backup recorder. In the latter, the data may be filled in if the uncertainty is less than that in the standard or if the correlation between stations for that parameter and that range can be shown to be 0.99 or greater. A comment containing the details of the relationship must be filed;
    (vi) The station is not a lake that normally has seiche or wind tilt (these are often studied, and a synthetic record will not be able to recreate the phenomena);
(e) Where the conditions do not meet these criteria, but trained personnel were on site for the whole period (for example, for desilting the stilling well) and recorded manual observations, the gap may be filled with these values and interpolated accordingly;
(f) Filling a gap in the original data record with synthetic data derived by correlation is not permissible. These can be used, however, for supplying data requests where the user is informed of the uncertainty involved. Such data must be carefully controlled to ensure they are not erroneously filed on either the local or central archives;
(g) A gap in a rainfall record may be interpolated only if it can be established that no rain fell during the period, by means of correlation with other gauges inside or outside the catchment area for which there is an established correlation and with a correlation coefficient of 0.99 or higher.

A professed reluctance to archive data that do not meet strict standards has the advantage of focusing an organization on taking steps to reduce the amount of missed data. As many root causes of missed data are preventable, a culture where people strive to improve performance in these areas makes a tangible difference to overall data quality.

Where it is necessary to fill gaps left by missing records, as it inevitably will be for some types of analysis, time spent on the estimation during the preprocessing stage may pay large dividends when the final data are used or analysed. It is also appropriate that these first estimates be made by the data collector with the benefit of recent and local knowledge. It is often the case, however, that reconstructing faulty records is time-consuming or that recovery requires access to processed data from another source covering the same period. A decision must be made as to whether the onus for the initial estimation of the missing record lies with the collector, or whether it could be synthesized more efficiently later in the process by using tertiary-processing routines.

Some attempt is normally made to fill data gaps by cross-correlation with nearby gauging stations, particularly those in the same river system. In the absence of reliable cross-correlation relationships, rainfall-runoff models, including the use of conceptual catchment models, may be used. All estimated data should be suitably flagged or stored in a separate archive.

Many river systems are significantly affected by human activities and these effects tend to change with time. For hydrological and water-resources studies, it is frequently necessary to try to isolate these artificial effects from the natural catchment response, that is, to try and obtain a stationary time series. This process requires extensive background information on all forms of direct and indirect diversions, discharges and impoundments in the catchment. Water-use effects may be aggregated into a single time series of net modifications to river flow. When these corrections are applied to the measured streamflows, a naturalized time series is obtained. Again, any modified data should be appropriately flagged.

9.8 VALIDATION AND QUALITY CONTROL

A somewhat artificial distinction has been made between primary and secondary processing procedures and validation procedures for the purposes of simplicity in this chapter. Data validation procedures commonly make comparisons of test values against the input data and will often exist at several levels in primary processing, data checking and quality control. They may include simple, complex and possibly automated checks being performed at several stages in the data-processing and archiving path. Some may also be performed on data outputs and statistical analyses by an informed data user.

As elements of quality control, the aim is to ensure the highest possible standard of all the data before they are given to users.

9.8.1 General procedures

While computerized data validation techniques are becoming more useful and powerful, it should be recognized that they can never be fully automated to the extent that the hydrologist need not check the flagged values. Indeed, to obtain the best performance, the hydrologist may need to constantly adjust threshold values in the program and will need to exercise informed and considered judgement on whether to accept, reject or correct data values flagged by the programs. The most extreme values may prove to be correct and, if so, are vitally important for all hydrological data applications.

Validation techniques should be devised to detect common errors that may occur. Normally the program output will be designed to show the reason the data values are being flagged. When deciding on the complexity of a validation procedure to be applied to any given variable, the accuracy to which the variable can be observed and the ability to correct detected errors should be kept in mind.

It is common to perform validation of data batches at the same time as updating the database files, normally on a monthly or quarterly basis. Some organizations carry out annual data reviews that may rerun or use more elaborate checking processes in order to carry out the validations after multiple batches have been updated to the archive. In some cases these will be run on the entire data set for a station. Such a system reduces considerably the error rate of data arriving at the central archive, where normally further validation is performed. Perhaps a more significant advantage of having these procedures in place is that the responsibility for the major part of the validation process is assigned to the observers themselves.

There is no doubt that visual checking of plotted time series of data by experienced personnel is a very rapid and effective technique for detecting data anomalies. For this reason, most data validation systems incorporate a facility to produce time-series plots on computer screens, printers and plotters. Overplotting data from adjacent stations is a very simple and effective way of monitoring inter-station consistency.

9.8.2 Techniques for automated validation

In order to review the wide range of techniques available for automated validation systems, it is useful to refer to absolute, relative and physio-statistical errors.

Absolute checking implies that data or code values have a value range that has zero probability of being exceeded. Thus, geographical coordinates of a station must lie within the country boundaries, the day number in a date must lie in the range 1–31 and in a numeric-coding system the value 43A cannot exist. Data failing these tests must be incorrect. It is usually a simple task to identity and remedy the error.

Relative checks include the following:
(a) Expected ranges of variables;
(b) Maximum expected change in a variable between successive observations;
(c) Maximum expected difference in variables between adjacent stations.

During the early stages of using and developing the techniques, it is advisable to make tolerance limits fairly broad. However, they should not be so broad that an unmanageable number of non-conforming values are detected. These limits can be tightened as better statistics are obtained on the variation of individual variables.

While requiring much background analysis of historical records, the expected ranges for relative checks (method (a) above) should be computed for several time intervals, including the interval at which the data are observed. This is necessary because the variance of data decreases with increasing time aggregations. Daily river levels would first be compared with an expected range of daily values for the current time period, for example, the current month. Since there is a possibility that each daily value could lie within an expected range, but that the whole set of values was consistently (and erroneously) high or low, further range checks must be made over a longer time period. Thus, at the end of each month, the average daily values for the current month should be compared with the long-term average for the given month. In a similar way, at the end of each hydrological year, the average for the current year is compared with the long-term annual average. This technique is of general applicability to all hydrological time-series data.

The method of comparing each data value with the immediately preceding observation(s) (method (b) above) is of particular relevance to variables exhibiting significant serial correlation, for example, most types of water-level data. Where serial correlation is very strong (for example, groundwater levels), multiperiod comparisons could be performed as described for method (a) above. Daily groundwater observations could first be checked against expected daily rates of change, and the total monthly change could subsequently be compared with expected monthly changes.

Method (c) above is a variation of method (b), but it uses criteria of acceptable changes in space rather than time. This type of check is particularly effective for river-stage (and river-flow) values from the same watershed, although with larger watersheds some means of lagging data will be necessary before inter-station comparisons are made.

For other hydrological variables, the utility of this technique depends upon the density of the observation network in relation to the spatial variation of the variable. An example is the conversion of rainfall totals to dimensionless units by using the ratio of observed values to some long-term average station value. This has the effect of reducing differences caused by station characteristics.

Physio-statistical checks include the use of regression between related variables to predict expected values. Examples of this type of checking are the comparison of water levels with rainfall totals and the comparison of evaporation-pan values with temperature. Such checks are particularly relevant to observations from sparse networks, where the only means of checking is to compare with values of interrelated variables having denser observation networks.

Another category of physio-statistical checks involves verification that the data conform to general physical and chemical laws.

This type of check is used extensively for water quality data.

Most of the relative and physio-statistical checks described above are based on the use of time series, correlation, multiple regression and surface-fitting techniques.

9.8.3 **Routine checks**

Standard checks should be formulated as part of an organization's data-processing procedures, and applied routinely to test the data. These will usually involve checking the data against independent readings to detect errors in time and magnitude. Instrument calibration tests are also examined and assessed for consistency and drift. A visual examination is made of sequential readings, and preferably, of plots of the data in the light of expected patterns or comparisons with related parameters that have also been recorded.

On the basis of these assessments, quality codes, if used, may be applied to the data to indicate the assessed reliability. The codes will indicate if the record is considered of good quality and, possibly, the degree of confidence expressed in terms of the data accuracy (9.10 on uncertainty). An alternative to quality codes is for data to have comments to this effect attached only if the data fail to meet the set standards.

At this stage, any detailed comments relating to the assessment should be attached to the data (or input to any comment or quality code database) for the benefit of future users.

9.8.4 **Inspection of stations**

It is essential for the maintenance of good quality observations that stations be inspected periodically by a trained person to ensure the correct functioning of instruments. In addition, a formal written inspection should be done routinely, preferably each year, to check overall performance of instruments (and local observer, if applicable). For hydrometric and groundwater stations, this should include the measurement of gauge datum to check for and record any changes in levels.

For a stream-gauging station, such inspections should include the stability of the rating curve, the inspection duties listed below and a review of the relationships between the gauges and permanent level reference points to verify that no movement of the gauges has taken place. It should also include a review of the gauging frequency achieved and the rating changes identified. As pressures on workloads, budgets and resources increase, it is not uncommon for so-called "discretionary" work such as gaugings to be neglected. This is an unfortunate, but understandable and sometimes inevitable, trend. It is vital, for the quality of data, that resources for gaugings be allocated and prioritized using rigorous and timely analysis of the probability and frequency of rating changes.

Every visit for stream gauging should include instrument checks and the rating checks mentioned above. These should be at an absolute minimum of two per year, and preferably more often to avoid the dangers of losing data and/or having data severely affected by problems such as silting, vandalism or seasonal vegetative growth.

The field programme should also provide for visits by a well-trained technician or inspector immediately after every severe flood in order to check the stability of the river section and the gauges. If there is a local observer, this person should be trained to check for these problems and communicate them to the regional or local office.

The duties of the inspector or field officer should include:

(a) Noting and recording any change in the observation site (a sketch map and digital photographs are useful);
(b) Making local arrangements for the improvement or restoration of the observation site, for example, removal of trees affecting raingauge catch;
(c) Checking the instruments and making any necessary field repairs or adjustments;

and, where applicable:

(d) Inspecting the local observer's record book;
(e) Instructing the observer on observation procedures and routine instrument maintenance;
(f) Emphasizing to the observer the importance of promptly filing complete and accurate returns;
(g) Briefing the observer on any special observations that may be required, for example, more frequent readings during storm and flood periods.

In order to perform his or her duty effectively (see (e) above), the inspector must be kept advised of errors made by observers, especially of any recurring errors made by a particular observer. Such advice should be forwarded regularly to the inspector by the officers responsible for the preliminary checking and error detection procedures. Results of these inspections should be included in the station history files.

9.8.5 Checking manually collected data

The basis of most quality control procedures for manually collected data is computer printouts of (usually) daily data by location or region. From such tabular arrays, it is easy to detect by sight those stations at which the data are consistently credited to the wrong day or subject to gross errors.

However, caution must be exercised in changing reported data. A study of the original report from the station, a check against the history of the station (as to the quality of its record), and an appraisal of the factors that produced the event (to ensure the data in question may not be a natural anomaly) are necessary before an apparent error is corrected. The alteration should be coded or commented to indicate that a change to the raw data has been made and that all of the above information must be documented.

Another method that can be used for checking the relative fluctuations of an observed element over a period is the use of various types of mathematical relationships, for example, polynomials. The computed value is compared with the observed value at the time. If the difference between the two does not exceed the previously determined tolerance, the data are considered to be correct. If the limits are exceeded, then further investigation is warranted.

For data collected manually and later entered into a computer, errors detected by either preliminary checking or error-detection procedures should be dealt with as follows:

(a) The correction should be made legibly on the original form and initialled by the person making the correction;
(b) The table or plot containing the erroneous data should be corrected, and the correction should be carried through to any other existing copies of the observation and to data that may have been derived from the erroneous observations;
(c) The station observer should be advised of the error. If the error is of a systematic type caused by the malfunctioning of instruments or the failure to follow correct observing procedures, the problem should be remedied through a visit by the inspector;
(d) A note of the error should be made in a register so that a running check can be kept on

observational quality at all stations and so that the field or inspection staff can be advised of stations with frequent errors.

9.8.6 Checking chart data

The ideal way of checking data captured by digitizing or scanning from charts is to plot a replica of the chart from the data file just before it is archived. If plotting processes can replicate the axes and scales, then the two documents could readily be compared visually on, for example, a light table. It should be noted that the plot should differ from the original with any corrections (such as to manual gauge readings) and other editing that may have been deemed necessary and valid.

If the processing system cannot provide a close replica (such as would likely happen with circular charts), then the plots need to be compared in rather more detail, with indicative points on each being measured for comparison, using a scale ruler if necessary.

9.8.7 Checking logged data

Data loggers have few original documents with which to compare the data they capture. However as the original, unedited data should have been plotted and filed in the station's processing file (Chapter 2), this document can be used in the same way as an original chart.

For errors detected in this process, as for initial checking, the data points should be annotated on the document(s), which should also be filed. Again, the originally recorded file should be archived, and a copy edited and updated to the archive.

9.9 SPECIFIC VALIDATION PROCEDURES

Techniques for quality control of data differ for various elements. The following are examples and discussion on techniques for several parameters.

9.9.1 Flow data

Since streamflow data are continuous in time and correlated in space, it is possible for the reliability of the data to be checked by interpolation and statistical methods. Qualitative checks may also be carried out using a number of techniques, as illustrated by the following examples:

(a) Rainfall plotted against flow or stage to detect any occurrences of freshets (or flood events) without significant rainfall and the reverse;
(b) Time-series plots of stage (hydrographs) or other parameters, with overplots of manual readings (including those from gaugings) during the period;
(c) Hydrograph plots of flow from stage series with ratings applied, with overplots of flow measurements from gaugings (plotted to the same scale);
(d) Cumulative plots (cusums) of annual rainfall overplotted with the monthly means for the complete record and other double-mass plots;
(e) Detection of steps in the data greater than a nominated value (that may vary according to the stage value). This will also normally detect spikes where a physical or electronic fault has produced a grossly high or low value (perhaps maximum possible or zero, respectively);
(f) Detection of missed values (that the software may otherwise interpolate);
(g) Printouts of periods of straight lines in a stage record that exceeds certain user-set lengths (can detect excessive compression or erroneous interpolation across gaps);
(h) Overplots of the same or related parameters (flow, stage, rainfall, turbidity) from nearby stations. If there is the opportunity for overplotting stations on the same river system, this can be particularly useful;
(i) Qualitative assessment by sight from plots, of the shapes of the hydrograph and their correspondence with normal patterns having regard to previous values and the given phase in the regime of the river.

Most of the hydrological database software packages have several of these techniques either built in or able to be run manually. Some also have the capability to run the processes automatically as script files (macros).

9.9.2 Stage (water level)

The techniques of tabular and plotted data, range and rate-of-change checks described above are used extensively for water-level data. Several of the plotting techniques can be applied to both stage and flow. However, as flow data can have errors associated with the stage-discharge ratings, it is important that stage be checked separately (and normally first).

The following points are the recommended minimum verification techniques for stage:

(a) Checks against the manual readings recorded by the observer at the beginning and end of each batch plus any others recorded at intermediate visits or by a local observer (normally done in preliminary checking);

(b) Plots of stage with overplots of any other stage values for the period that have been entered into the database, such as from flow gaugings or water quality data sets (this will depend on the database);

(c) A qualitative check of the hydrograph shapes and events, looking for suspicious features such as straight lines, steps, spikes or freshets, floods and recessions in conditions where they would not be expected.

In addition, a number of qualitative checks, as described above for flow, should be carried out. Any apparent inconsistencies should be investigated to the extent possible:

(a) First, checks should be carried out to determine whether there were any comments already recorded in the database or in the logbook for the station, or any evidence of processing. The observer, field technician or data processor may have already checked this event and/or noted the actual or apparent cause;

(b) Depending on the inconsistency noted, the following items could be checked with the field observer or against the evidence of the data processing. Some may require specific investigation on site at the station, and with previous and succeeding batches of data:
   (i) If there is a "sluggish" peak and recession, a field check of the stilling well and intake pipe for silt blockages may be required;
   (ii) Steps or spikes in the record may indicate that the sensor, float, logger or recorder has malfunctioned or had undergone some interference;
   (iii) A data batch that appears higher or lower than data on either (or both) sides may have been wrongly processed with erroneous corrections against manual readings or sensor offset;
   (iv) Straight lines in the record can indicate gaps due to missing data that have been wrongly interpolated, or instrument or sensor problems, for example, sticking float cable or minimum or maximum range reached;
   (v) Increasing flows between freshets or floods (uphill recessions) may indicate wrong stage corrections made, or alternatively weed or sediment build-up on the channel, the latter indicating work required on the stage-discharge rating;
   (vi) Regular diurnal (daily) fluctuations may indicate problems with the sensor (if it is a pressure type, moisture may be present in the system), icing on the control (will need correction to convert to flow) or something real, such as channel evaporation or daily freeze-thaw in the catchment.

Naturally, the best verification techniques are limited in value, unless there is appropriate investigation of the queries they raise coupled with appropriate corrective action, including filing of the results. These can be either as comments filed with the data or through the assigning of informative quality codes.

Automated methods for carrying out many of these techniques are available as part of hydrometric software packages or can be developed within them. Some may be available to run automatically on near-real-time telemetered data. An example screen from such a package is shown in Figure I.9.3.

Note: An interesting plotting format is shown in Figure I.9.3 which, although it depicts flow, is equally valid for water-level data. The plot covers a 13-month period and is designed to reveal any discontinuities that may appear between successive annual updates of a master database.

9.9.3 **Rainfall**

As rainfall is a very important and highly variable hydrological phenomenon, there are many rainfall stations and hence large amounts of data. Most countries now have well-established systems for quality control and archiving of rainfall data.

A system used by the Meteorological Office in the United Kingdom for the processing of daily rainfall is described in the *Guide to Climatological Practices* (WMO-No. 100). The errors occurring in the collection and processing of rainfall data are almost universal; therefore, this system should serve as a model for many different environments.

The reliability of a system that uses inter-station comparisons is related to the network density. In areas having sparse coverage of raingauges, there is an increasing tendency to install rainfall radars (3.7). Areal values derived from such installations provide excellent data for both validation and rainfall data for areas with no rainfall stations. Another application of radar data for validation purposes is encountered in areas subject to intense localized thunderstorms, for example, most tropical countries.

The event-based nature of rainfall means that there are a number of ways of plotting and presenting the

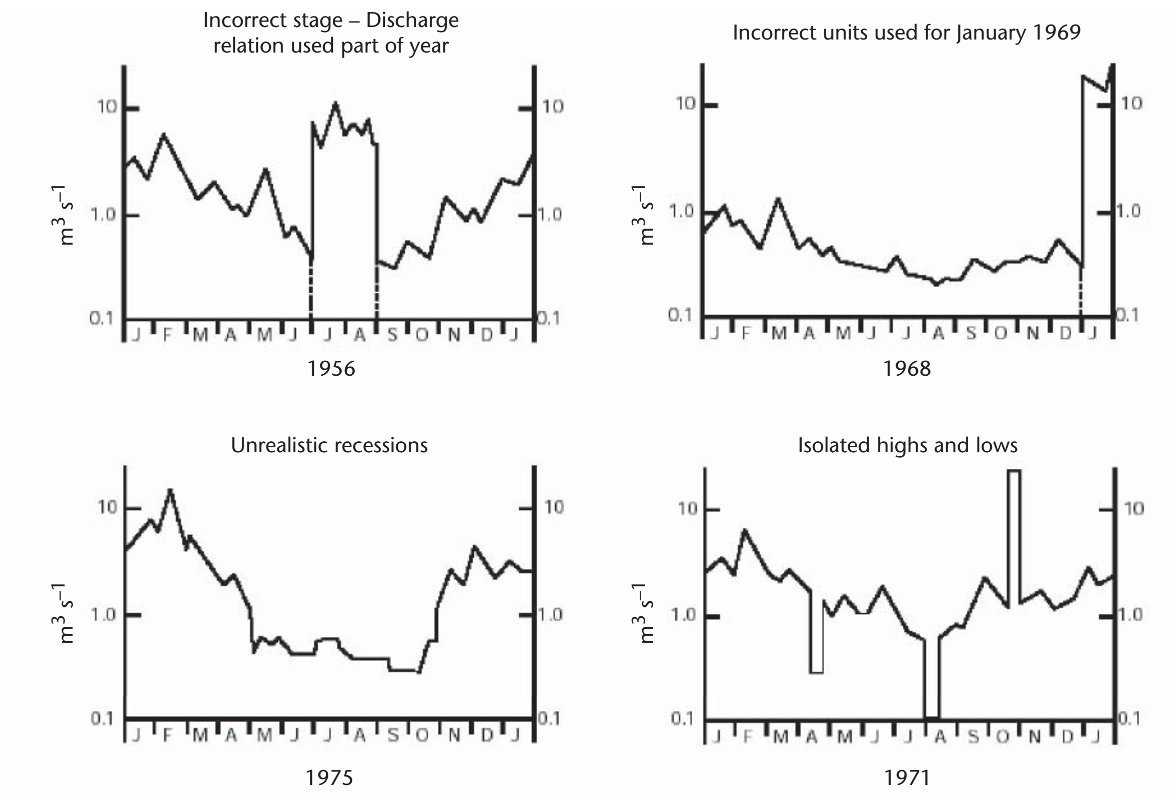


Figure I.9.3. Time-series plots for checking streamflow data
(Source: World Meteorological Organization/Food and Agriculture Organization of the United Nations, 1985: *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management* (WMO-No. 634, Geneva)

data for verification. These include accumulating the readings over various time intervals and plotting them as separate events or cumulative totals. The following techniques can be used:

(a) Plot the data as, perhaps, hourly totals and overplot them with stage or preferably flow from a nearby flow station. The smaller the station's catchment, the more meaningful the comparison is likely to be;
(b) In addition to the above, overplot previous maxima;
(c) Plot cumulative daily totals (cusums) for a period such as the year, and overplot this with similar plots from adjacent stations, and with the cumulative totals from the check gauge. Figure I.9.4 shows a typical double-mass plot;
(d) Overplot cusums as above with cusums of mean annual weekly or monthly data and thus compare the current year or season with the longer-term averages. Also plot the maxima and minima for comparison;
(e) Plots may also be prepared to allow manual checking of spatial variation. A simple means is to plot station positions, together with their identification numbers and data values. Such a technique is used widely for monthly and annual checking of rainfall and groundwater data on an areal basis. More complex software can interpolate data in space and plot isolines.

Any apparent inconsistencies in the data should be investigated to the extent possible:

(a) First, checks should be carried out to determine whether there were any comments already recorded in the database or in the logbook for the station, or any evidence of processing. The observer, field technician or data processor may have already checked apparent problems and noted the actual or apparent cause;
(b) Depending on the inconsistency noted, the following items could be checked with the field observer or against the evidence of the data processing. Some may require specific investigation on site at the station, and with previous and succeeding batches of data:
    (i) If the data show lower precipitation than expected, this may indicate that the sensor, logger or connections may have malfunctioned or undergone some

interference; likewise if the sensor appears to have failed to record some rainfall events;

(ii) If the rainfall events appear to be attenuated (spread over a longer period), this may indicate blockages in the gauge due to debris or interference, or it may indicate accumulations of snow that melt gradually;

(iii) A data batch that appears higher or lower than data on either (or both) sides may have been wrongly processed with erroneous corrections against manual readings or the wrong units or scaling.

9.9.4 Climatological data

The validation of climatological data by methods of inter-station comparison can be questionable in many cases because of the sparsity of the climatological stations. Thus, the basic validation techniques applied are range checks, rates of change checks and, of particular importance, consistency checks between related variables observed at the same site.

For example, all reported psychrometric data should be checked or recomputed to determine whether the dry bulb temperature exceeds or equals a reported wet-bulb or dewpoint temperature; depending on which data are available, the dewpoint temperature and/or relative humidity should be computed and checked against the reported value.

Similarly, empirical relationships between evaporation-pan or lysimeter data and other observed variables could give broad indications of suspect data at the validation stage. More sophisticated adjustments for the evaluation of evaporation and evapotranspiration are normally made in subsequent primary-processing stages.

For all climatological data, station and variable codes should be tested for validity and, where relevant, sensor-calibration values and ranges should be output with suspect values.

Comprehensive details of climatological quality-control procedures are presented in the *Guide to Climatological Practices* (WMO-No. 100).

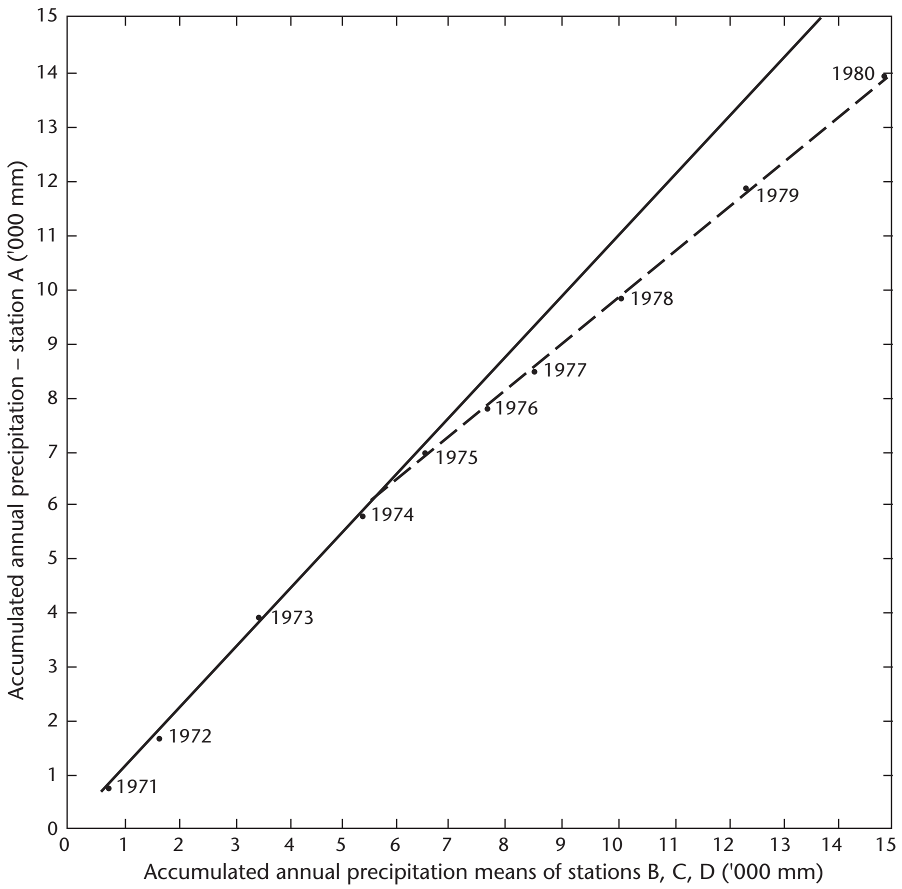


Figure I.9.4. Double-mass plot. Double-mass curve showing the relationship of annual precipitation at station A to the mean of three nearby stations. Note the abrupt change that occurred in 1975.

9.9.5 Snow and ice data

Whereas the water equivalent of falling snow caught in raingauges may be validated along with rainfall data, other snow and ice variables are more difficult to treat.

Data on the extent of snow cover may be validated only by a time-consuming manual synthesis of field observations, aerial-survey data and satellite imagery (3.7.4, 3.12 and 3.13). Techniques to perform automated interpretation of satellite imagery for snow extent (as well as depth and water equivalent) are being developed. While these techniques show promise, there are still problems both with differentiating between snow and cloud cover, and of insufficient image resolution. Further, unless a GIS is used, data on extent may be stored only as manually-abstracted catchment-area totals.

Data on snow depth and water equivalent demand much manual validation and verification by integrating data from snow courses, snow gauges and conventional precipitation gauges. The large spatial variation in snow cover makes inter-station comparison difficult. However, there are techniques that can be used to estimate the statistical reliability of snow-course observations under conditions of melting snow. Degree-day factors are widely used for correlation purposes and, where snow melt represents a significant proportion of river flow, established relationships between runoff and snow-water equivalents may be used. Air (and water) temperature relationships are valuable not only for the computation of degree-day factors, but also for the validation of ice-cover and thickness data and in the forecasting of ice formation and break-up dates.

Snow and ice data, whether quantitative or qualitative, are important validation data for a wide range of other hydrological variables. For example, anomalous river-stage data during the winter months may be explained and possibly corrected if background data indicated the nature and extent of ice conditions.

9.9.6 River-gauging data

As each gauging is processed, there are a number of items that need to be checked, including accuracy of key entry and correctness of meter calibrations, as mentioned previously. There are a number of verification techniques for individual gaugings that can be applied:

(a) Some computation programs provide overplots of horizontal velocity and measured depths. While these parameters are not fully related, most channels show some relationship, and the person carrying out the gauging should be able to verify that the plots are sensible and identify any outliers. This illustrates the desirability of the computation being done as soon as possible after the gauging and preferably on site;
(b) Checking of the cross-section area and shape together with the water level from previously surveyed cross-sectional data may be feasible at some stations;
(c) The theoretical uncertainty should be calculated in accordance with ISO 748 in order to verify that the technique used is capable of providing the required level of uncertainty. This will normally be done by the computation program;
(d) Plotting the gauging on the rating curve may provide some degree of verification. If it plots off by a significant margin, then some other evidence of a likely rating change should be sought, such as a flood event high enough to trigger a bed change, seasonal weed growth or debris;
(e) With a stage-discharge relationship, the correctness of the stage used to plot the gauging is as important as the correctness of the discharge value. Therefore the stage should be verified against the value recorded by the water-level recorder (if one exists);
(f) The location of the gauging cross-section should be verified as appropriate to the data requirement, with regard to the possibility of water abstractions, tributaries and artificial discharges, under-bed flow, weir leakage, etc.;
(g) For ADCP gaugings, parameters that need to be checked for correctness include whether water salinity and density measurements have been performed, instrument depth off-set has been accounted for, depth range capability of instrument is compatible with the depth of the river, Doppler ambiguity settings are correct, the presence of moving-bed has been checked, extrapolation techniques are in accordance with those required or recommended, ratios of measured to unmeasured flow are sufficient, sufficient transects have been measured and adequate coefficients of variation have been adopted. It should also be verified that procedures are in accordance with those required or recommended.

For all measurements, the validation program should check for the use of valid station, instrument and method-of-analysis codes and, where possible, for valid combinations of these. It is also

Table I.9.1. Checking water quality data against physio-chemical laws

1. Dissolved solids

All results expressed in mg l^{-1} should comply with the check:
$0.1 \times TDS > [TDS - (Na+K+Mg+Ca+Cl+SO_4 + 4{,}42\ NO_3 + 0.61(Alk) + 3.29NO_2 + S_1O_2 + F)]$
NO_2, S_1O_2 and F are optional, i.e., validation check can be used without them, but they should be included, if available.

2. Ion balance

(a) Standard requirements (8 to 12 ions)
Ions should be converted to meq l^{-1} and subjected to the check:

$$\frac{[\text{Cations} - \text{anions}] \times 100}{[\text{Cations} + \text{anions}]} < 3\ \%$$

where cations = $Na+K+Mg+Ca+NH_4$

and anions = $Cl+SO_4 +NO_3 +HCO_3 +NO_3 +PO_4 + F$

PO_4, NH_4, NO_2 and F are optional, i.e., the balance can be checked without them;

(b) Minimum requirements (6 ions)

This rough check can be used where only major ions have been measured.

Results should be converted to meq l^{-1} and be subjected to the check:

$$\frac{[\text{Cations} - \text{anions}] \times 100}{[\text{Cations} + \text{anions}]} < 10\ \%$$

where cations = $Na + Mg + Ca$

and anions = $Cl + SO_4 + HCO_3$

3. Conductivity

0.55 conductivity (µs cm^{-1}) < TDS < 0.7 conductivity (µs cm^{-1}) where TDS = Total Dissolved Solids

4. General checks for water quality

Total solids	> total dissolved solids
Total solids	> settleable solids
Saturation of dissolved oxygen	< 200
mg l^{-1} dissolved oxygen	< 20
BOD_5 (total)	> BOD_5 (filtrate)
BOD_5 (total)	> BOD_5 (settled)
COD	> BOD
Total oxidized nitrogen	> nitrate
Total hardness	> temporary hardness
Total cyanide	> cyanide – excluding ferrocyanide
Total phenols	> monohydric phenols
Total phenols	> polyhydric phenols
Total dissolved chromium	> chromate
Oil (total)	> oil (free)
Oil and grease	> oil (free)
Total oxidized nitrogen	= nitrate plus nitrite
Total hardness	= Ca + Mg
Total phenols	= monohydric and polyhydric phenols

Source: World Meteorological Organization/Food and Agriculture Organization of the United Nations, 1985: *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management* (WMO-No. 634) useful for any plots or printouts to contain this information and any relevant calibration coefficients.

Additional information on aspects of discharge measurement is available in the *Manual on Stream Gauging* (WMO-No. 519).

9.9.7 Water-quality data

The very wide range of water quality variables has resulted in the use of relatively simple validation procedures for water quality data. Such criteria are normally absolute checks of analysis codes, relative checks of expected ranges and physio-chemical checks of determinant relationships. If range checks are being devised in the absence of historical data, it should be noted that the valid ranges of many variables will be associated with the purpose for which the sample was taken, and the location of the sampling point. Thus, the levels of dissolved salts found in water samples taken from drinking water sources will be less than those found in effluents or in brackish or marine water bodies.

Physio-chemical tests are very effective and, hence, widely used for water quality data.

Examples of typical physio-chemical tests performed for normal and specific (effluent) samples are shown in Table I.9.1.

If some variable values have been determined in the laboratory and all of the relevant associated data are available to the computer, they may be recomputed for verification purposes. All water quality data and the station, variable and analysis codes may be checked for validity and, where possible, for validity of their combination.

9.9.8 Sediment data

As with water quality data, mass-balance calculations may be performed if sufficient data exist. If a sediment rating curve exists for the section sampled, the departure of the sampled value from the curve may be estimated for its statistical significance and/or plotted for manual scrutiny.

The sediment gaugings and the rating curve should be examined to determine if there are any changes in the rating according to the seasons; and if so, the sampling programme should be reviewed to aim for at least approximately equal amounts of data from each season. Similarly, the proportion of gaugings on the rising and falling stages should be examined and attempts made to sample in both conditions.

9.10 RECORDING UNCERTAINTY

The informed data user will always be concerned with understanding the accuracy of the data in question, as this will govern the confidence that people can have in the data and the derived information. There are many ways of expressing accuracy, many of them imprecise and sometimes ambiguous. Statistical uncertainty provides a means of objectively expressing "accuracy" as a stated range or percentage range with a given probability of occurrence.

Several of the ISO standards concerned with hydrometric techniques cover uncertainty in some detail as it applies to each topic. The ISO publication *Guide to the Expression of Uncertainty in Measurement* (ISO, 1995) is recommended as a general guide to the topic. Guidance on the estimation of uncertainty of discharge measurement is provided in the *Technical Regulations* (WMO-No. 49), Volume III, Annex, Part VIII.

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CHAPTER 10

DATA STORAGE, ACCESS AND DISSEMINATION [HOMS G06]

10.1 INTRODUCTION

The availability of sufficient good quality data underpins all aspects of hydrology, from research, to water resources assessment through to a wide range of operational applications. The definitions of "sufficient" will vary from one application to another, and are discussed elsewhere. Discussed in this chapter are the issues of "good quality" and access to data, as well as availability of data to a wide range of users.

10.1.1 The importance of data

The culmination of data collection in hydrology, from precipitation measurements, water-level recordings, discharge gaugings, to groundwater monitoring and water quality sampling, provides a data set that can be used for decision-making. Decisions may be made directly from raw data measurements, derived statistics or the results of many stages of modelling beyond the raw data stage, but it is the collected data that form the basis for these decisions.

Raw data – whether field forms, charts or reports – must be available after processing. Some errors in reporting and processing may not come to light until scrutinized by users. It may also be necessary to check transcriptions from the original or to re-assess the collector's interpretation of a doubtful trace. Records from a particular site may need to be verified by re-sampling in response to development activities, or changes in technology may result in an upgrading of standards. In either event, the data may require reprocessing. Thus, the original data must be securely archived. The storage should be kept away from the electronic database and should be physically secure.

A data set is clearly of great value as it is inevitably collected through a huge commitment of time and money. The management of these data is therefore important work in itself and this work must be performed effectively in order to maximize the results of this investment. A well-established and well-managed hydrological archive should consolidate the work put into data collection to provide a source of high-quality and reliable data for tens or hundreds of years into the future. A poor-quality archive, due to lack of forethought in its foundation or poor management, can lead to years of excess data collection or modelling work, and subsequent poor decision-making. The archive could become redundant within a very short time. Moreover, poor-quality data and databases will result in suboptimal planning decisions and poorly designed engineering structures.

Data integrity is also a major issue. Often the key to understanding the success or limitations of work in all fields of hydrology is an understanding of the quality of the data on which this work is based.

Of course the scale of data management depends on the scale of the operation: a large-scale and detailed hydrology project will require more complex management techniques and computer storage than a smaller scale project measuring a limited set of variables over a short period of time. Other factors affect the scale on which data are managed; as well as volumes of data there are often budgetary constraints, where limited staff time can be spared for archiving and funds are unavailable for large data management systems. The capacity of staff to manage data can be a constraint and the level at which data management is performed is dependent on the experience or skills of the personnel.

Despite the potential variety due to scale, however, there are a number of essential aspects that are common to all hydrological data management systems. This chapter as a whole describes each of these aspects of data management in detail, with a focus on the general approach, and occasionally highlights the reality at each of these extremes of scale.

10.1.2 Data management processes

There is a definite flow path that hydrological data must follow from the point of collection, as input into the system, through validation to dissemination and use in decision-making processes. This path is essentially the same regardless of the scale of operation and the level of technology used for data management, and is demonstrated by the schematic diagram in Figure I.10.1. The list in Table I.10.1 summarizes some of the data sets existing at various stages of the data management process. This is an overview of the entire data management process. Some of the aspects of this process are discussed in detail in Chapter 9. In the present chapter, the focus is on data storage, access and dissemination and demonstration of where they fit in the data management process.

A full description of the recommended procedures for storage and cataloguing of climatological data is given in the *Guide to Climatological Practices* (WMO-No. 100). While hydrological data require a somewhat different treatment for storage efficiency, many of the same considerations apply.

The vast quantities of climatological and hydrological data being gathered by many countries may preclude storage of all original data. However, copies can be made in media (for instance, electronic scan) that require a small fraction of the space required for the original documents; the original materials may then be discarded. Storage conditions for any of the media on which data are stored should minimize deterioration of stored records by excessive heat, temperature fluctuations, high humidity, dust, insects or other pests, radiation and fire.

Where possible, duplicate sets of records should be kept, one in the main collection centre and the other at a regional centre or at the observer's office.

The various types of input data and the data-processing and quality-control process applied to them are described in Chapter 9. Input data can originate from manuscript observer records, chart recorders, automatic data loggers and manuscript sheets or digital files storing instantaneous discharge measurement (gauging) information, including river section, depth and velocity profiles, often with associated descriptive text information.

Table I.10.1 summarizes the processes involved in data management from inputting raw data measurements through to disseminating processed data, as well as the data involved in these processes.

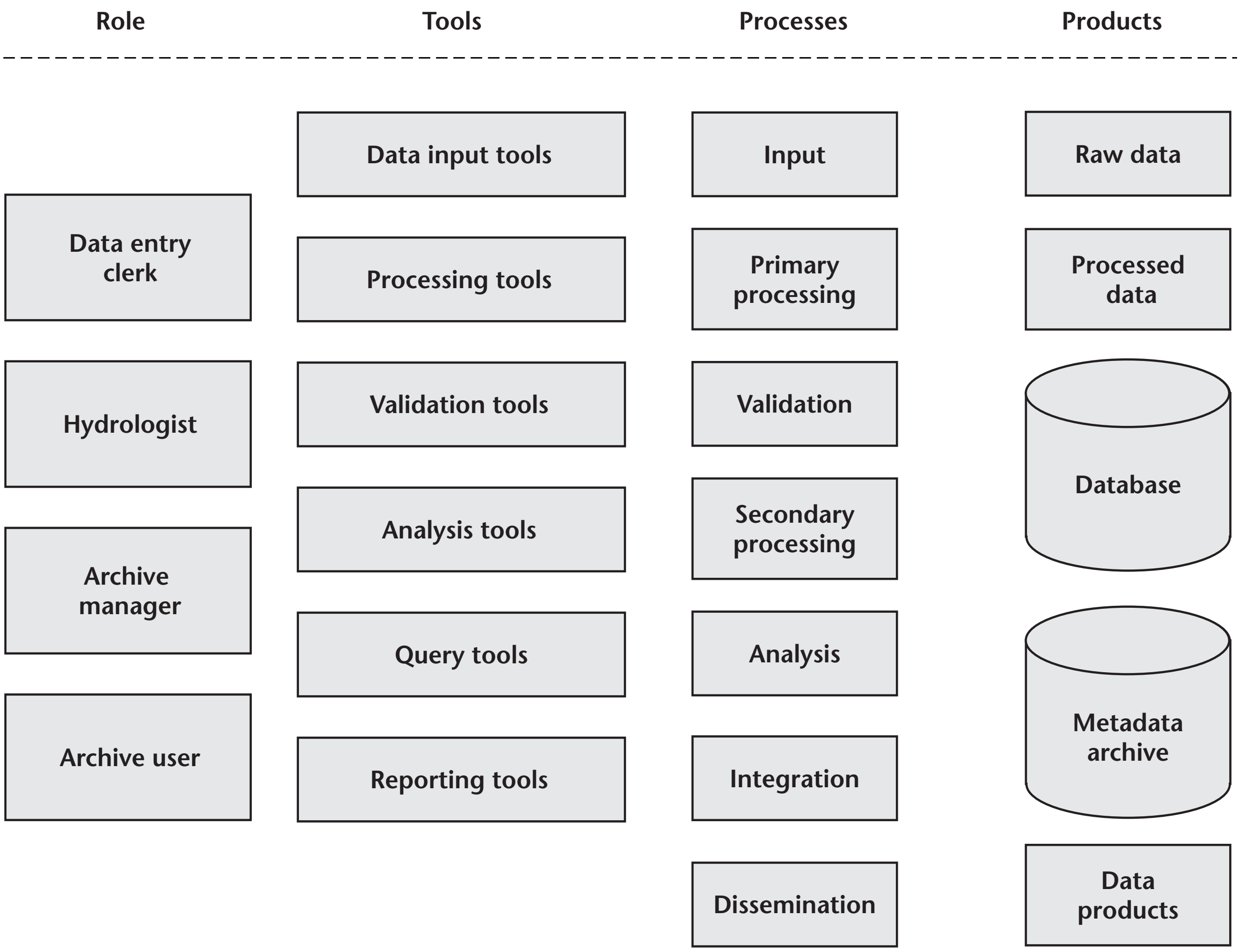


Figure I.10.1. Data management scheme

Table I.10.1. Processes involved in data management

Process	*Description*	*Examples of data type involved in the process*
Input	Data are obtained from the source or instrument, via manual recording, data logging, digitization or other method, and transformed to the appropriate format for storage.	Gauge readers' book/sheet (daily or sub-daily stage read manually from a staff gauge, with additional notes to describe any necessary context) Raw data file from automated data logger linked to measurement probe – often in binary/custom format Charts from water-level recorder Sheets/digital files storing instantaneous discharge measurement (gauging) information, including river section, depth and velocity profiles and descriptive information
Processing of raw data	Data stored in manual or digital forms, often both	Digital files of data digitized from charts Data series within databases or digital files of manually entered gauge records and gauging information Digital files of data series converted from custom logger files, usually text files
Validation	Raw data are checked for erroneous values and edited to produce a corrected raw data series.	Data series within database at each stage of editing/validation Text describing changes including methods used and reasons for editing
Secondary processing	This stage includes infilling of missing data where appropriate, conversion to secondary intervals (for example, calculations of mean and total series), creating rating curves from new discharge measurements and conversion of raw stage data to flows or reservoir storage.	Data set for each new series created in conversion process Rating equations created from discharge measurements, and associated text describing decision-making process in creating rating equation. Rating equations will generally change over time, and so a good rating history must be maintained.
Security and archiving	Data must be archived in such a way as to be accessible but secure, and well documented and indexed.	Metadata allowing quick and easy access to data sets, as well as a full index of the information available
Integration with other data	Allowing display of data with other sources of data such as GIS data sets	New datasets such as spatial rainfall coverage derived from point raingauge data or groundwater surface maps from borehole data
Data dissemination	Data are distributed as required and in appropriate forms to modellers, decision makers, public bodies, etc.	Summaries of data, yearbooks, etc. Increasingly, data dissemination is via websites.

It is clear that there is potentially a large number of data sets at each of the stages of the data management process, and decisions must be made concerning which data should be stored, and how to do so in an effective hydrological archive. A description is provided below of the storage of data, analysis of these data and the production of information, access to the information and the dissemination of the information to the variety of users.

Having completed the data-processing and quality-control phases described in Chapter 9, the data will be archived in a form that will have associated with it a range of analysis and product derivation tools, as well as access and dissemination tools.

10.2 DATA STORAGE AND RETRIEVAL

10.2.1 Storage of data

One of the most important considerations within the field of hydrological data management is which of the numerous data sets produced should be stored. There are many stages in the process of data management from recording to dissemination and each of these stages can represent one or more distinct data sets. If one were to store every possible permutation of data in this process, the result would be a confusing and unwieldy archive. At the other extreme, if a hydrological archive existed only as a static data set of processed and validated data, there would be no means of understanding how the data had been derived or measured, or the potential limitations of the final data set. For example, a processed flow data set provides no information about the means of measurement, the process of deriving flow data from water-level data, or whether the data had been edited and how this editing was performed. It is therefore necessary to decide on a feasible data storage mechanism that falls somewhere between these two extremes.

The basic consideration for the level of detail of data storage is that of reproducibility. In any hydrological project, however large, it is necessary that the steps from raw data to final processed data set be understood, and reproduced if required. Users of the processed data should be able to quickly and easily see the process through which data have passed, and understand the potential limitations. This does not imply that every change to the data set must be retained for posterity, rather that raw data sets should be retained, and that changes and assumptions made during validation and processing should be documented and stored. It is also important that users of the data be able to differentiate between original data and data that have been added to fill gaps, or edited data.

Once again, the level at which this data storage is performed will be determined by a number of factors, such as available storage space, availability of funds for storage and documentation, and the availability of staff. There will inevitably be a trade-off between completeness of archive and resources spent. At the most complex end of the spectrum, a large and complex hydrology project may use a data storage system that allows fully automated auditing of all changes to data sets in the system, storage of dates and times when changes are made as well as identification of the user making them, and allows edits to be sequentially rolled back to recreate any version of the data set that existed. A simpler system may contain merely the raw data set and the final data set with a file of notes documenting the decisions and edits made. However, in both cases the process is essentially the same:

(a) Raw data files must be kept, whether these are in a hard format (gauge reader books, recorder charts) or digital format (raw data logger files or telemetered data);
(b) All processed data sets should be associated with descriptive metadata records detailing the origins of the individual data set and linking each to the data set from which it is derived;
(c) Important stages of data processing should be stored, even if the processed data are only an interim stage between raw data and disseminated data. The decision about importance will be determined by the scale of the data management system. For example, if a raw water-level data series is to be converted to a series of monthly mean flows only, it would be sensible at least to store the validated water-level data set, and the derived daily flow data, in addition to the raw data and final monthly mean flow;
(d) Wholesale changes to parts of each series should be documented against the data set, for example, noting the application of a datum to a period of a stage record, or conversion of a period of a stage record to flow with a rating curve, which will itself exist as a data set;
(e) Changes made to individual data values, for instance interpolating missing data values or editing values separately, should be documented against each data value changed, with notes against the record as a whole to indicate to the data user that the series has been altered;
(f) The resulting data set will then have a comprehensive catalogue of what has been edited and why, allowing any data user to be able to both understand the reasons for and methods of changing raw data values, and to reproduce the data set from the raw data.

10.2.2 Storage methods

One of the most important considerations when archiving data digitally is the database to be used. The term database is often used misleadingly, and in hydrological circles and elsewhere is often used in reference to both the database system itself and the software for querying the database and displaying and analysing the data.

Both of these are important aspects of any archive individually and will be dealt with separately in this chapter.

A database can be described simply as a filing system for electronic data. Any organized assembly of digital data is, in effect, a database. Several important aspects of these assemblies define which database is most appropriate in a particular case, relating directly to the principal concerns of data managers set out in 10.2.1.

10.2.2.1 Important criteria for data storage systems

When developing data storage systems, a number of important criteria must be considered, including:

(a) Security – this includes management of access and administrative rights for the various users;
(b) Ease of maintenance;
(c) Costs, including initial outlay and recurrent costs including any software licences required, maintenance and storage;
(d) Ease of query;
(e) Power of existing data query tools;
(f) Ease of development of additional query tools;
(g) Ability to include/link to other data sources or data display software, such as GIS;
(h) Suitability alongside existing information technology (IT) infrastructure/requirements and staff capabilities;
(i) A metadata system that provides adequate information on the data in the database;
(j) Ability to allow networked/remote access – linking to network and web servers.

Of course each instance of a hydrometric archive will have different levels of importance for each of these aspects and again the extremes are depicted. The advanced requirements of a large national network, such as automated, real-time data loading, links to sophisticated analysis tools and multi-user access from numerous distributed organizations in turn require substantial expensive technical support, training of users and often bespoke development of tools. The database must be run securely on a high specification machine and be able to be backed up automatically to tapes in a fireproof safe. A small project database may need to be operated by a single hydrologist. In this case loading, editing and analysis of the data must be simple operations that can be quickly learned. The resulting database may need to be small enough so that it can be sent by e-mail to other users. A small nation's hydrometric archive may be data essential to the country's social, environmental and financial future, but may, of necessity, have to be run on a very limited budget. Collecting data is expensive and money spent on overly specified computing systems might detract from the purpose of the archive: that of measuring and publishing good quality hydrometric data. However, a database must be sustainable: secure, simple to manage on the available infrastructure, whilst providing the necessary tools.

The types of database (here, electronic data management systems) can be divided into the following categories.

10.2.2.2 Simple ASCII files

The simplest type of database could be a set of ASCII files containing data, indexed on a PC or network drive. A separate file could be used for storing data for a particular time series, perhaps with a separate directory for storing the data for each station. Advantages of such a system are that it costs no more than the computer on which data are stored, is very simple to set up, with little or no knowledge of computers, and that files can easily be found, with the text format allowing any user to read data immediately, and to store any sort of data that can be subsequently read. Disadvantages include the obvious insecurity of the system, the limitation of a single-user storage system, the lack of existing analysis and graphing tools for data, and the difficulty to develop tools to work with the data. However, many organizations still maintain such a system, which could be considered appropriate for a small company storing copies of data that are archived elsewhere when no analysis is required, security is not an issue but low maintenance is of paramount importance.

10.2.2.3 Bespoke database formats

Many data storage systems, particularly those developed before the surge in computer technology in the late 1990s, use their own format for storing data. These are often highly compressed formats allowing large volumes of data to be stored on the small disk spaces that were available then. In addition, writing customized methods for accessing data from specific formats can allow very fast retrieval and saving of data, as all of the overheads associated with allowing generic data access are avoided. Besides these advantages of bespoke systems, an organization that has compiled its own database has also developed a considerable body of knowledge and would be able to cater efficiently to its needs in data storage and viewing, as well as analysis tools. Disadvantages include the inability to interface with or incorporate other available technologies (a feature of more generic systems) and the cost of maintaining the developed tools as the platforms and operating systems on which they run evolve. In addition, there is the risk of the organization relying on detailed in-house knowledge, which may lead to difficulties if there is no system of knowledge transfer, or this knowledge somehow becomes lost.

10.2.2.4 Relational Database Management Systems

Relational Database Management Systems (RDBMS) are, as their name suggests, more than just databases. They are generally a specific file format for data storage (the database itself) together with management protocols and software access tools. The most complex of these can feature integral query, reporting, graphing and publishing tools. Several well-known RDBMSs are available on the market. They are well used around the world and are therefore well tested and supported, both by the vendors and the users. Skills for development of additional tools are readily available. The security, level of support, availability of query tools, price and the like vary between systems.

10.2.2.5 Specialized hydrometric database systems

The database systems described above are just that: generic tools for storing data. They must be adapted by the user to meet his or her specific needs. It is most likely that the needs of almost all hydrologists can be fulfilled by a specialized hydrometric database system. These are essentially off-the-shelf software products (although in some cases there may still be considerable work involved in installing the software), which can be purchased or otherwise acquired. They mostly comprise a database system, of one of the types described above, which has been adapted to cope specifically with common types of hydrological data. For instance, database tables and access routines that specifically handle hydrological data types and store appropriate descriptive information and metadata may have been created. Commonly the system is provided with software to allow the data to be managed, edited and graphed, and this software is much easier to use than the database itself. In addition many of the data management tools are extended to include analysis tools, for instance, tools to produce flow duration curves from flow data, and statistical tools for fitting distributions to flood peaks. These database software systems include HYDATA, HYMOS, TIDEDA, HYDSYS and WISKI.

The pros and cons of these systems fall into the categories mentioned in 10.2.1. The commonly available systems generally vary in scale. The smaller systems can be easier to install and run and are less expensive to buy and maintain. Larger scale systems tend to be more expensive, but have more advanced functionality, and are often built around a larger scale database with increased security, although this can often have associated licence costs for the database software. The choice of system therefore depends on user needs, and ability to purchase and maintain a database system.

10.2.2.6 Database management skills

Databases can be managed by a single person or by teams of many people, but the processes performed generally require particular skills, which determine the role of the person involved in the process. Some of these skills are listed in Table I.10.2.

10.2.2.7 Summary

To summarize, there are numerous types of digital data storage systems. While most hydrologists' needs would be filled by one of the specialist hydrometric database systems available, some advanced users may have additional requirements that would be better met by a customized database system. Most importantly, a database system is purely a means of storing digital data. Good archive management can only be achieved by good management of data.

Table I.10.2. Database skill requirements

Role	*Description*
Data entry clerk	Little understanding of hydrology or IT required, though data may often have to be downloaded from data loggers or extracted from different file formats
Hydrologist	Validation work requires expert knowledge of hydrology and the local hydrological regimes. Analysis work requires expert hydrological knowledge.
Archive manager	General archive management and dissemination requires hydrological knowledge. Integration of archive data with other processes requires both hydrological and IT skills.

10.2.3 Types of data and information to be stored

This section describes in more detail the particular information that should be stored in a hydrological archive. Perhaps the best way to consider how an archive should be arranged is to imagine approaching an archive with no prior knowledge of the meteorological conditions, sizes of rivers, catchment characteristics, gauging station network, water use within catchments or volumes of data. It should be possible to quickly gain an understanding of the entire contents of the archive, then to easily retrieve exactly the data required. Archive users should be able to fully appreciate all of the changes that have been made to data and should be able to retrieve information on data availability, summary statistics and full data sets quickly. This allows users to start work on a data set at any point in its management process with minimal effort. In addition, the archive system should make the documentation of work a simple and efficient process. The production of further data sets, for inputs into models, into further data processes, for distribution to separate data users, or for the creation of publications such as yearbooks, should also be a simple and quick process for the archive manager.

10.2.3.1 Archive metadata

On viewing a hydrological archive, the first level of data seen by a user should be data describing the archive itself. These are in fact metadata – information about the archive itself that should actually be published by the data manager as a means of disseminating information about the archive. These data could take the form described in Table I.10.3.

These archived metadata could be provided by a complex computerized system, perhaps with a GIS interface to allow access to the data and automatically updated summaries of data availability through which the user could browse, or this could be as simple as a folder of papers, which is the responsibility of the archive manager. In the case of the latter, the folder should be regularly updated as new stations or new data are added.

10.2.3.2 Station metadata

When users of the archive are familiar with the data holdings they will require further information. Station description data are important to provide the context within which the station operates. These data can also provide a shared resource for data users to understand, for instance, the implications for the data of measurement devices used, or the morphological setting of the station, and for the station management staff to store information concerning location of station, access information, datum and addresses of local operating staff. Most of the data in Table I.10.4 can relate generally to meteorological stations, gauging stations or other measurement sites, though some fields are specific to hydrological river gauging stations.

Information on the development of the WMO core metadata standard can be accessed at: http://www.wmo.int/web/www/WDM/Metadata/documents.html.

A summary of the status of hydrological metadata systems can be found in Global Runoff Data Centre, Report 31 (Maurer, 2004).

Table I.10.3. Descriptions of data held in archive

Data type	*Description*	*Examples*
Archive description	Brief text describing the background and aims of the data monitoring project	Name and description of the project, start date of the project/archive, aims of the project, summary of dissemination routes
Geographical maps	Maps providing the physical context for the archive's data	Catchment boundaries, gauging station/meteorological station location and other data measurement locations, river network, lakes and other features of importance
Data summaries	List of data sets and availability	Summary, by data type, of data held in the database, referencing locations of measurements, plus additional data held, for example, derived spatial data and GIS data from other sources, plus a summary, for each data set, of data availability over time at an appropriate scale

Additional information on metadata database standards is available from the following Internet sites:
– USGS – Federal Geographic Data Committee's "Content Standard for Digital Geospatial Metadata: http://www.fgdc.gov/metadata/metadata.html Dublin Core Metadata Element Set, Version 1.1 http://dublincore.org/documents/dces/
– ISO 8459-5 Information and documentation – Bibliographic data element directory – Part 5: Data elements for the exchange of cataloguing and metadata: http://www.iso.org/iso/en/CatalogueDetailPage.CatalogueDetail?CSNUMBER=27176&ICS1=35&ICS2=240&ICS3=30

A number of examples of metadata for hydrological systems are available and can be accessed at:
– Global level: http://www.watsys.unh.edu/metadata/

Table I.10.4. Examples of station metadata

Metadatum	*Description*	*Examples*
Identification	Current identification information for the station, and summary of the purposes for which the station is used	Station name(s), station number(s), catchment name, waterbody name, hydrometric area name, elevation, catchment area, primary purpose, secondary purpose, primary measurement method (for example, weir type), high flow measurement method, general description of station
Location	Information about the geographical position of the station	Latitude/longitude (or position in local coordinate system), nearest town/landmark, benchmark location and height, information about landowner, routes, accessibility, appropriate access time, information concerning access in flood periods, etc.
Operator	Information about the organization operating the station, if operated by another, for example, regional organization	Operator name, contact details, responsibilities, etc.
Observer	Information about the staff taking measurements at the station	Observer name, contact details, responsibilities, starting date, frequency of visit, reporting method and interval
Station history	Description of the history of the station, showing any changes that may affect data measured	Date opened, date closed (for closed stations), location history, operator history, equipment history, datum history
Equipment/telemetry	Information describing any data loggers or automated telemetry systems used at the station	System names, manufacturer, purpose, reference for associated literature, date installed, antenna heights, etc., reporting interval and frequency, parameters reported, additional descriptive information
Statistics	Summary statistics of data at the station	Statistics, values, period to which statistics apply, date calculated, etc.
Graphics	Pictures of station and surrounding area	Picture, description, date, references to digital pictures files, etc.
Data set history	Information describing the data sets produced for the station	Parameters measured, derived series produced, flow path for data measured at the station, summary of data availability
Gaugings and ratings history	Descriptive information concerning instantaneous discharge measurements and rating equation development – actual gauging data should be stored in database	Description of river section(s) used for gaugings, history of changes to section through movement of section/erosion, etc., drawings of section, description of issues

– National level: http://www.epa.gov/Region8/gis/data/r8_hyl.html;
– State level: http://www.isgs.uiuc.edu/nsdihome/webdocs/st-hydro.html; http://www.wy.blmgov/gis/hydrologygis-meta.html

10.2.3.3 Time-series data

The majority of data used in hydrology is time-series data, the measurement of a variable at a fixed place over time, including rainfall, streamflow, water level, reservoir storage, borehole water level, soil moisture and pH. At a single station (or geographical location) there are often multiple time series of data measured and each of these may have different characteristics. Each station should store a summary of the time series measured at the site (data set history in Table I.10.4) and the attributes of time series should be noted against each of these (Table I.10.5).

10.2.3.4 Real-time data

Data collected by some form of telemetry and required for real-time operational use, for example, flood forecasting, reservoir operation or monitoring low flows for ecological purposes, may have to be archived and accessed in a different system than that collected for regular monitoring or long-term assessment of water resources. Such telemetered data generally must go through some fairly simple data-validation process before being archived for input to real-time models. Such validation may be as simple as checking that each incoming data value is within pre-set limits for the station, and that the change from preceding values is not too great. Thus, 15-minute rainfall data must always be a positive number, but less than the highest ever recorded 15-minute rainfall for the region of interest plus perhaps 10 per cent. River-level data must also be greater than bed level or crest level of the gauge weir, and a suitable maximum value can generally be set. In addition, from analysis of previous major flood events, an appropriate maximum rate of rise for any 15-minute period can be established. Where data fall outside of these limits, they should generally still be stored in the raw data file, but flagged as suspect, and a warning message displayed to the model operators.

Where suspect data have been identified, a number of options are available to any real-time forecasting or decision support model being run:
(a) The suspect data could be accepted and the model run as normal, although this is rarely a reasonable option;

Table I.0.5. Time-series data characteristics

Data field	*Description*
Name	Ideally, a time series should be appropriately named allowing instant recognition of what is stored, for example, daily mean flow or monthly total flow as opposed to fow series 1 or flow series 2
Time-series type	Data being measured, for instance rainfall, flow or water level
Measurement statistic	Indicates the derivation of the data, or the statistic being stored: mean, instantaneous, total, maximum, etc.
Unit	Indicates the unit in which the data are being stored
Interval	Frequency at which measurement is made, or period over which statistic is calculated, for example daily, monthly, every 15 minutes. Irregularly recorded data are also considered and often denoted as an instantaneous time series.
Period of record	Start (and sometimes end) date of the data series
Limiting statistics	It is often recommended that an initial estimate of the maximum and minimum data values for a series be set before measurement commences as a means to validate the data. This is particularly useful if automated validation methods can pick out values outside the recommended range. Following extreme measurements, these limiting statistics can be reset more accurately. A level for maximum rise and fall within the series can also be useful if the methods used for data validation can usefully use these statistics, as can setting limits to more complex derived statistics. These statistics should be for guidance only, as data outside these limits can be valid and should not be excluded.
Further time-series level data	Other information that can apply to a time series as a whole can also be stored at this level, such as the water day of measurements (indicating which period derived average and other values should be calculated) and datum if this is appropriate to the entire period of data.

(b) The model can be run treating the suspect data as missing, that is, assuming that there has been no further rainfall during the period in question, or having no observed river level and flow data against which to test a forecast flow;
(c) The missing data could be substituted with some form of backup data. Thus missing river levels could be extrapolated from previous values, and missing rainfall data could be infilled by reference to other operating gauges, or mean seasonal values assumed.

How missing data are dealt with will vary from situation to situation and will depend upon the modelling requirements. The topic of modelling is dealt with in Volume II, Chapter 6.

10.2.3.5 Spatial data

Almost all of the data discussed above are either descriptive metadata or time-series data of measured attributes. A further type of data is discussed here. Spatial data are data that have a substantial geographical component. Examples include maps of gauging station sites, digital elevation models and isohyets of rainfall. Spatial data can be displayed in GIS and these are often used to integrate hydrological and spatial data sets.

Geographical features are represented in GIS coverage in various forms (Figure I.10.2):
(a) Polygon – data exist as shapes of areas, such as countries or basins;
(b) Line – data appear as lines with associated attributes, for example, rivers;
(c) Point – data exist as individual points, for example, river-gauging stations and raingauges;
(d) Grid – region is divided into grid squares and the attribute (for example, rainfall) over this square is stored together with other attributes.

The characteristics of these geographical features are called attributes, for example, each polygon of a geological coverage may contain attributes such as lithology or aquifer type.

For the purpose of this discussion spatial data for hydrology can be divided into two simple categories:

Physical maps

Physical maps are an invaluable resource in hydrological studies and still constitute the principal source of spatial data in many countries. They can include specialist maps, such as those showing soil coverage, geology or rainfall, or they can be national maps showing multiple feature types such as towns, roads, contours and rivers. Physical maps should be considered a central part of a hydrological archive, and are a useful first point of reference providing valuable contextual to actual gauging station and meteorological data. They should be stored accordingly, ideally in appropriate map chests, racks or mountings. The map archive should be well documented, including:
(a) Map reference numbers and originator/source;
(b) Map title and description;
(c) Scale;
(d) Projection;
(e) Number and name in map series;
(f) References.

Dissemination of physical map data can be difficult, as there are often restrictions due to copyright. However if photocopies of maps, or portions thereof, are to be disseminated, the above information should be included to allow maps and legends to be traced and interpreted.

If physical maps are created in an archive, for instance runoff maps from gauging station flow data, the existence of these maps, and the details, should be published in the appropriate place. This could be in hydrological data books or through national or regional mapping agencies.

Digital data

Over the past 10 years or so there has been a widespread move from physical maps to digital maps. Developments in technology have allowed maps to be digitized and used in GIS. Within these systems it is far easier to manipulate and integrate maps. It is also easier to extract information from them and disseminate changes.

Many digital maps may be simply digitized versions of physical maps. For instance, the contours on a normal general usage map could be digitized to a line coverage, or a map of soil types could be digitized to a polygon coverage. As with any data management process, the origins of data, as well as any edits made, should be carefully documented so that users of the resulting data can be aware of its origins.

In addition, digital maps can be created. For instance, a gridded coverage of rainfall data can be created from point source raingauge data by the use of various processes. Contour lines, when accurately digitized, can be extrapolated to create a digital elevation model grid of topographic heights. Using contours or a digital elevation model, gauging station catchment boundaries can be manually added to a new line coverage. If such derived maps are stored as part of a hydrological archive, the same precautions regarding reproducibility mentioned in 10.2.1, should be followed. Each derived map should have associated archived metadata describing the process used to create it. Any significant and useful intermediate data sets created should be archived as appropriate.

10.2.3.6 Management considerations

When managing hydrological data and information it is important to include the following:

(a) Validation or quality-control flags (9.8 and 9.9);
(b) Text comments from users/data processors (9.7 and 9.8);
(c) Audit trail – information on the introduction of data to the database and any following changes or adjustments (Chapter 9).

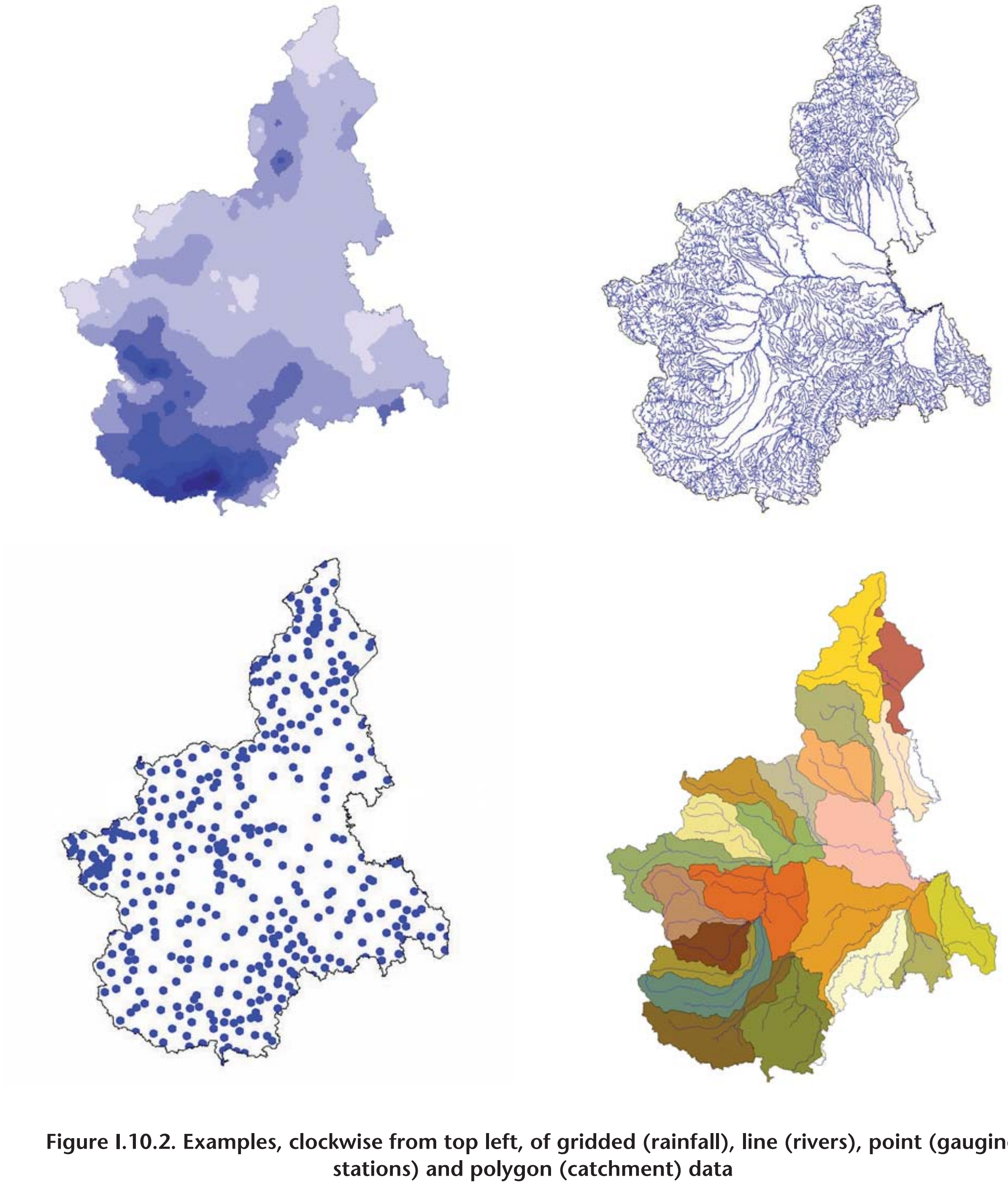


Figure I.10.2. Examples, clockwise from top left, of gridded (rainfall), line (rivers), point (gauging stations) and polygon (catchment) data

These types of data and information should also be stored and made readily accessible.

10.2.3.7 Controlling data flow

The importance of proper control of incoming data sets has already been mentioned with regard to data-entry operations. The need to be aware of the status of all data sets in the various stages of validation and updating is equally vital. This is particularly true when suspect data have been queried and some response is awaited from hydrological staff in charge of quality control.

Initially, the entire monitoring process may be manual, but ultimately some functions may be automated as part of the general computerized data-handling activities.

Automation allows routine monitoring of data-batch status, validation summaries and the physical disposition of data on the system, for example, the tape or disk volume numbers and the data set names. Such control is essential where large quantities of data are handled.

Data-control personnel should be appointed with the following responsibilities:

(a) Logging of incoming data batches and the routing of these batches to the appropriate data-entry system;
(b) Monitoring and logging data-entry status and the subsequent submission of data for initial validation and processing;
(c) Routing validation reports to appropriate hydrological personnel and receiving edited data;
(d) Repeating steps (a) to (c) until all data batches have been accepted for updating purposes;
(e) Forwarding monthly and annual summary statistics to appropriate agencies and personnel.

The exact nature of the tasks depends upon the extent to which individual users have access to data for editing purposes. In online systems where users are responsible for their own quality control, central responsibilities are reduced. However, such users must have some means to indicate that quality control has been completed and that data sets are ready for further processing.

10.2.3.8 Updating procedures

Most archival databases in hydrology are updated in at least two stages. These stages are shown in Figure I.9.2. The first stage is the cycle of monthly updates corresponding to a standard reporting period. The extent to which the four first-stage activities are split into separate computer runs is dependent upon the user and the physical resources of the system. If most files are archived on tape, it probably would be impossible to perform the complete set of monthly processing with one program because too many tape drives would be required. There may also be a policy not to compute derived values, for example, flows or potential evapotranspiration, until all the basic data have been checked manually.

For the end-user, the main outputs from this first updating phase are the monthly summary reports. For database management purposes, the most important results are the updated annual workfiles. If this first phase system handles data only in monthly blocks, it may be necessary to maintain incomplete data files. This need arises from the use of computer-compatible recorders, where the recording medium is normally changed at irregular intervals. Thus, when processing month 1, there may be several days of month 2 on the recording medium. In this case, the month 2 data are saved on a temporary file until the complementary data are available during month 3. The cycle is repeated, and a complete month 2 file and a new incomplete month 3 file are generated. This problem is rarely encountered with manual reporting or telemetry stations. If the computer-compatible medium requires pre-processing, there exists an option to perform the splitting and subsequent aggregation of months on the pre-processing (micro) computer before data are submitted to the main processing machine.

After passing the validation checks (and being subjected to any necessary primary processing) (Chapter 9), the monthly data batches are added to the current annual data file. Data not passing validation checks must be manually scrutinized, and, where errors are verified, relevant actions must be taken as indicated in Figure I.9.2.

In order to provide an adequate turnaround of data, it is generally necessary to start processing each monthly data batch from the tenth to the fifteenth day of the following month. If processing is not started by this time, there is a danger that the total data handling, entry and processing for the annual file updates may become backlogged.

The purpose of the annual updating cycle is to add the annual workfile to the historic database. This transfer carries with it a change in status of the data from a working data set to a quality controlled hydrological reference set. Thus, it must be ensured that as many data queries as possible are resolved before the annual updating takes place. Output from the annual processing stage may be utilized for hydrological yearbooks.

10.2.3.9 Compression and accuracy

A significant operation in all database updating is the compression of data to make optimal use of storage space. The technique of packing is described in the *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management* (WMO-No. 634). However, packing techniques tend to be machine specific, and several other data-compression techniques are used in various hydrological database systems. These are:

(a) Integer numbers are used in storage, which are suitably scaled for output purposes. For example, daily rainfalls, measured to a precision of 0.1 mm, could be stored in tenths of a millimetre (an integer) and subsequently divided by 10 for output. The storage requirement is halved. A normal integer uses two bytes of storage compared with the four bytes required to store a real (decimal) number;

(b) The use of unformatted (binary) data files instead of normal ASCII files. In addition to requiring less space, binary data are more rapidly stored and retrieved;

(c) The use of a counter for repeated constant values. Thus, a period of 10 days without rainfall need not be stored as a set of 10 zeros, but as a repeat factor of 10 followed by the zero value;

(d) A more sophisticated version of the above method is to completely remove redundant data. Redundant data are derived from the over-recording of hydrological phenomena by some types of field instruments, in particular, by fixed interval recorders. For example, in the sequence 40, 50, 60, it is apparent that the central value can be derived by interpolation from the adjacent values. Thus, software can be developed to scan data, eliminating all those values that may be linearly interpolated within a defined tolerance range. This technique greatly reduces the storage requirements but leads to no significant loss in the information content of the data. In New Zealand, the use of the TIDEDA system (HOMS component G06.2.01) has resulted in two- to twelvefold savings in storage space;

(e) The use of relative rather than absolute data values. For example, water level in a borehole may be quoted in absolute elevation terms or, more economically, in relation to some local datum or average water level. Only the difference from the previous data value need be stored. These various forms produce smaller numbers that may be stored in correspondingly smaller storage locations. Some balance must be made in the levels of data compression employed. Increasing efficiency in the use of storage is gained at the expense of executing compression and expansion routines each time the data are stored or retrieved. The correct level of data compression should reflect the relative limitations of storage space and computation capabilities, and software development skills, at each installation. With regard to the accuracy of the data stored, it is exceptional for any hydrological data to be observed to an accuracy of greater than one part in 1 000. For this reason, many hydrological databases store data only to an accuracy of three or four significant figures. Thus, a flow computed as 234.56 $m^3 s^{-1}$ may be stored as 235. Such a practice is also used to save data storage space.

10.2.3.10 Physical-file organization

Sequential file organization is simple, may be used on all forms of storage medium and is suited to time-series data that are input and most frequently accessed in a sequential manner. Indexed sequential files are very attractive for the storage of most hydrological data as the inherent sequential nature of the data is preserved on the storage medium, but the ability exists to access directly individual, or groups of, records.

Random-access, like indexed-sequential organization, is only relevant to disk or diskette files, but requires higher system overheads in terms of storage volumes. Individual records may be accessed directly and more quickly if they are accessed in a random manner. By the use of cross-references (pointers), data in random-access files may be related in complex and effective ways.

If a hydrological database is being developed to support online (interactive) data manipulation, files must be available on disk, and the use of indexed-sequential or random-access files should be feasible. Indeed, their use is probably essential to obtain acceptable response times when handling large amounts of data.

Where online data access is not a priority, it may be worthwhile to keep single variable time-series data, such as water levels or rainfall, on sequential files because they are usually searched to abstract a time sequence of data. For multivariate time-series files, there are some advantages in indexed-sequential or random-access organization.

If a certain variable is measured at a few stations only, then all stations will need to be searched to locate the values in a sequential file. In some types of random-access file, it is possible to store a pointer with each variable value, and the pointer indicates the location of the next station record that contained a value for the same variable. This location could then be accessed directly. Such a technique is advantageous for water quality data where the variables observed vary widely both between stations and for the same station at different times.

Data stored on magnetic tape, the most common format for large database archives, must be held in a sequential manner. However, when files are transferred from tape to disk, any of the range of access methods described above may be used. Whichever access method is used, it is recommended that all large database files be unformatted (binary).

Some database systems utilize a mixture of techniques to maximize storage and retrieval efficiency. This is done by storing large groups of sequential data in single records of random-access or indexed-sequential files. By using this method, each daily or even hourly station-year data may be stored as one physical record in a random access, or indexed sequential, file. To retrieve the data for a given month, the relevant station-year record may be accessed directly on the disk. This record is then transferred to an in-memory buffer from which the data for the correct month may be rapidly read. Some mention should be made of the use of database management systems (DBMS). These systems invariably rely on the use of random-access files. Some caution is recommended in their use unless exact data input and retrieval formats are known (and relatively fixed), and there exists sufficient software support. An evolutionary approach to DBMS use is recommended.

Many agencies are now evaluating the use of RDBMS for the joint storage of data and other information. Advances in this field should be closely monitored.

10.2.3.11 Logical file organization

There are two aspects of the logical organization of data – the major groupings, which determine the number of files, and the sets of variable values that are included in the records of each file.

A comprehensive hydrological database will contain the following groups of files:

(a) System reference files that include the code lists (dictionary file) used to check data input, encode data for storage and decode data for output. If some form of spatial data coding is used, then hydrological and/or geographical referencing files will also be needed;
(b) Station description files ranging from simple files relating station numbers to station name, type, location and instrumentation, through to detailed files, such as the complete data for well or borehole logs;
(c) Calibration files containing the detailed background information necessary to compute derived variables, normally on a station-by-station basis. Examples include rating curves for river-flow stations and calibration coefficients for climatological and water quality sensors. Some data are independent of stations, for example, current-meter calibration coefficients and reference tables for theoretical incoming radiation and sunlight hours;
(d) Time-series files containing the series of observations made at hydrological stations. They may be single- or multiple-variable series and may be observed at regular or irregular intervals of time.

The relationship of these various groups of files is shown in Figure I.10.3.

From an organizational point of view, it is possible to combine all information of types (b) and (c) into common files or to split each type into current and historic files. This has the advantage of enabling a standard format and size to be used for the current files. The decision is largely governed by the amount of descriptive data to be held in the computer files compared to that held in manual files.

It is useful to consider the various alternatives available for storing different types of time-series data in the same physical file.

At the simplest level, all stations are allocated their own files with data ordered sequentially in time. This technique is suitable for small data sets or for keeping archived data on tape. However, because hydrological networks may contain several thousand stations of various kinds, this simple system becomes extremely difficult to manage and support with large numbers of files.

At a higher level, that used for most hydrological database systems is the use of files containing many stations, where each file contains data of a different type. This may be hydrological, for example, daily discharge values or mixed time-series, for example, several variables at fixed intervals. In the first case, a daily discharge file, for example, would contain all daily discharge data for the entire hydrological network. The file, if sequentially organized, would be ordered by station and, within each station, by time. In the second case, all daily data would be included, regardless of the hydrological type, and the file would be ordered by both station type and station number. Both these cases are encountered in the Water Data Storage and Retrieval (WATSTORE) system (Kilpatrick, 1981), which comprises five large files. One file contains the station header (description) data. Of the remaining four, three are grouped by hydrological type (water quality, peak flow and groundwater-site inventory) and the fourth, grouped as time series, is the daily values file. This latter file contains data observed on either a daily or continuous basis and is numerically reduced to daily values. Instantaneous measurements at fixed time intervals, daily mean values and statistics, such as daily maximum and minimum values, may also be stored. In 1981, this file contained 190 million daily values, including data for streamflows, stages, reservoir contents, water temperatures, specific conductances, sediment concentrations, sediment discharges and groundwater levels.

At the highest level of integration (other than the utilization of DBMS) are systems that handle all types of time-series data in one common storage format and that store all time-series data in one physical file. Such an approach, used in the New Zealand TIDEDA system, greatly simplifies software development for data management and retrieval tasks because the storage format is standard. Similar data-processing and storage systems, both also HOMS components, are the United Kingdom HYDATA and the Australian HYDSYS systems. Details on how data are manipulated by these data-processing and storage systems can be found in the *Guidelines for Computerized Data Processing in Operational Hydrology and Land and Water Management* (WMO-No. 634).

10.3 DATA RETRIEVAL

10.3.1 Data analysis tools

Data analysis tools can be an integral system working from the same database, or separate manual and computerized tools for performing tasks required to create an archive (see Table I.10.6).

In the development of data extraction tools, it will be necessary to identify the needs/requirements of users and ensure that the tools developed meet these requirements. This will need to take into account data requirements for:

(a) A single series – for example, daily or monthly flow data for a defined period;
(b) A multiple series – for example, flow data from a group of stations or coincident rainfall and streamflow data;
(c) For a single value across a series (such as for modelling or GIS display) – for example, the annual peak discharge for a site or the average annual rainfalls for a number of sites.

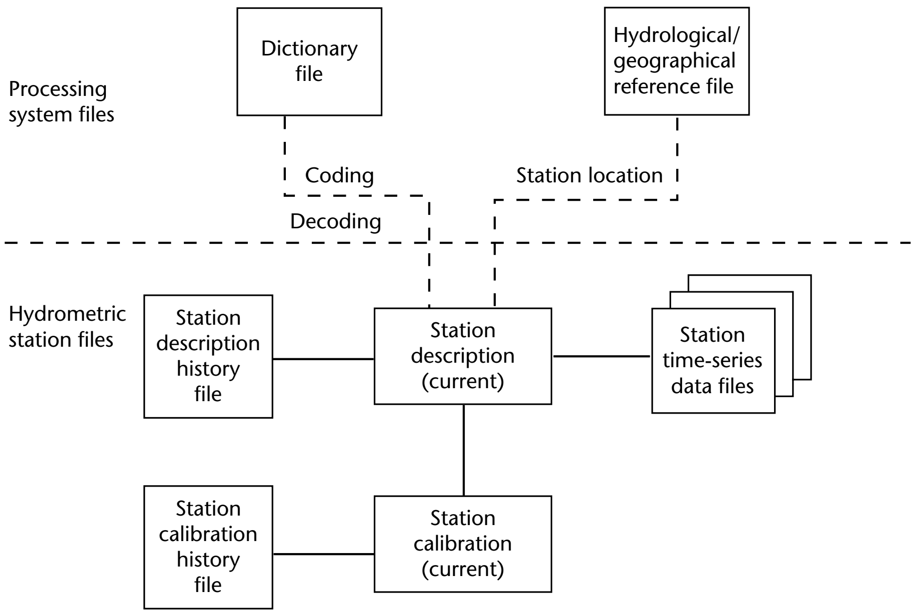


Figure I.10.3. Relationship of hydrometric station data files

Table I.10.6. Data analysis tools

Tool	*Description*
Data input tools	Manual typing, software and hardware for downloading data from loggers, reformatting software, standard spreadsheet tools for formatting and storing data, automated real-time data management tools
Processing tools	Primary processing: hardware and software for digitizing chart records, for example; secondary processing: software tools for conversion of water levels to flows, for example
Validation tools	Software for viewing graphs and editing data, software for producing double-mass curves/maximum-minimum hydrographs, etc.
Analysis tools	Software (including spreadsheets) for producing statistics such as flow duration curves
Query tools	Software tools for retrieving specific data values or statistics from archived data
Reporting tools	Software tools for producing reports/data for dissemination from archived data

Data and information should be able to be retrieved from the database in a range of formats, again targeted to meet the needs of the users, and can includ the following:
(a) Descriptive file – a range of information from different sources describing the data that are available and their characteristics;
(b) ASCII files (10.2.2.2);
(c) Comma-separated value (CSV) files – This is a delimited data format that has fields or columns separated by the comma character and records or rows separated by newline. Fields that contain a special character (comma, newline or double quote) must be enclosed in double quotes. However, if a line contains a single entry which is the empty string, it may be enclosed in double quotes;
(d) Other formats as defined by the user.

10.3.2 Extraction of single variable data

There are occasionally inefficiencies in storing data as multiple time series. These inefficiencies relate to the wide range of variables that may be observed at each site and the way in which data may be retrieved.

Consider climatological data that, after its initial use in the computation of potential evapotranspiration, may be accessed only to retrieve individual variables. Such retrievals are commonly required for the spatial interpolation and/or mapping of data, for example, temperature data for snow melt computations or radiation data for assessing crop-production potential. The retrieval process would be inefficient because all stations must be searched even though the variable was observed at only a limited number of them.

It has been seen (10.2.3.10) that such problems can be overcome by using data pointers stored with each value, which give the location of the record containing the next value of that variable. However, if this technique is used for many variables, the overhead for pointer storage becomes very high. A solution to this problem is to remove important variables – those frequently accessed individually – and to store them as single variable time series. This practice is standard with rainfall data observed at climatological stations. This extraction of important variables is best performed during the annual update when validated data are transferred to the historic archive.

It should be stressed that the decision to perform single variable extraction is dependent upon the anticipated way that data will be retrieved. The frequent retrieval of values for a specific variable suggests the extraction of that variable from the multiple variable set. The fewer the stations at which such a variable is observed, the more inefficient is the multiple variable search, and the stronger the case for a single variable format.

If, as is usually the case with water-quality data, retrievals are made for several variables relating to the same observation time, then the original multtiple variable format probably remains the most convenient.

10.3.3 Data retrieval system

Data retrieval is discussed in detail in the *Guidelines to Computerized Data Processing in Operational Hydrology and Land and Water Management* WMO-No. 634). The ability to rapidly retrieve selected data sets is one of the fundamental advantages of electronic hydrological data processing. Efficient retrieval systems allow the hydrologist or water resources planner to concentrate on data analysis by minimizing the previously time-consuming tasks of locating, collating and manually processing data. A comprehensive retrieval system should contain the following features:

(a) A wide range of data-selection criteria – Typically these should be by variable, basin, station, time period and variable value (or range). In particular, it should be possible to select data on the basis of any combination of these criteria;
(b) Data interpolation/aggregation in time and space – Perhaps the most important of these options are the interpolation of irregular into regular time series and the aggregation of short time-interval series into totals or averages of a longer time base, that is, conversion of hourly into daily values or daily into 10-day values.
If some form of geographical/hydrological referencing system is used, spatial data adjustments may also be made;
(c) Computation of simple statistics – Some facility should exist to enable the computation of simple statistics for the period(s) of record selected. This would include totals (if relevant), means, standard deviations and ranges. More comprehensive statistics – cross-correlations, multiple regressions, probability analyses, etc. – may be offered as part of the standard retrieval system, or the selected data may be passed to a statistical package (or user program) as described below;
(d) Selection of output format – This feature should allow for the direct output of data in (specified) tabular or plotted format and for the creation of data files in formats suitable for further processing. In this latter case, the retrieved data set may be stored for input to statistical packages or user-specific application programs.
A particular output format may be suitable for the interchange of hydrological data on a national or international basis;
(e) Selection of output device – There should be broad flexibility in the choice of output device. At a minimum, this should include a line printer, VDU and disk file. If available, a plotter should be selectable. Data to be transferred to tape or floppy disk is normally first stored on hard disk and transferred with a separate utility requiring several user-specified variables.

It is important that retrieved data, particularly that intended for printed tabular output, retain their codes and flags relating to status and reliability (9.3).

Background information relating to the general reliability of data and/or unreliability during specific periods should be available to the user through the station description file (2.5.2) or the data catalogues.

Data retrievals may be generated in three ways:

(a) Routine data retrievals – These are station data summaries and statistics produced on a monthly and annual basis;
(b) User-specified retrievals – After consulting hydrological yearbooks or data catalogues, users may request data retrieval by using an appropriate form, and the retrieval is submitted as a normal batch job. This relies on computer operators or other technicians to input the retrieval request using the data retrieval software.
The retrieval request form should allow for a wide selection of output media;
(c) Online (interactive) retrieval of data – There are several modes of online specification of data retrievals which, because of their potentially wide use, are discussed below.

As discussed earlier in this chapter and as shown in Figure I.10.4, the existence of an online master database allows the interactive retrieval of data. However, except for systems with small amounts of data or very large disk storage capacities, the major part of the database must be stored offline. Thus, the direct interactive mode is usually suitable only for retrieving limited quantities of most recent data. In some systems, remote users can send messages to the computer operators to request the mounting of a particular offline database volume. However, such requests are rarely satisfied immediately, and this can become very inefficient in terms of terminal usage and communication costs.

Probably the most efficient means of online specification of retrievals is the two-stage process. In the first stage, an interactive program allows the user to specify retrieval requirements, and in the second stage this request is automatically submitted as a batch job and the output is obtained later. The format of an interactive machine/user interface is called a menu system. Executing large data retrievals in batch mode is much more efficient in terms of the computer's ability to allocate its resources, particularly for the extraction of data from offline volumes.

The above discussion relates primarily to online retrievals of data from hydrological-inventory systems. However, the ability to review data being collected and stored for real-time systems is perhaps a more fundamental requirement. Retrieval options range from telemetry interrogation of individual or groups of field stations to the plotting and display

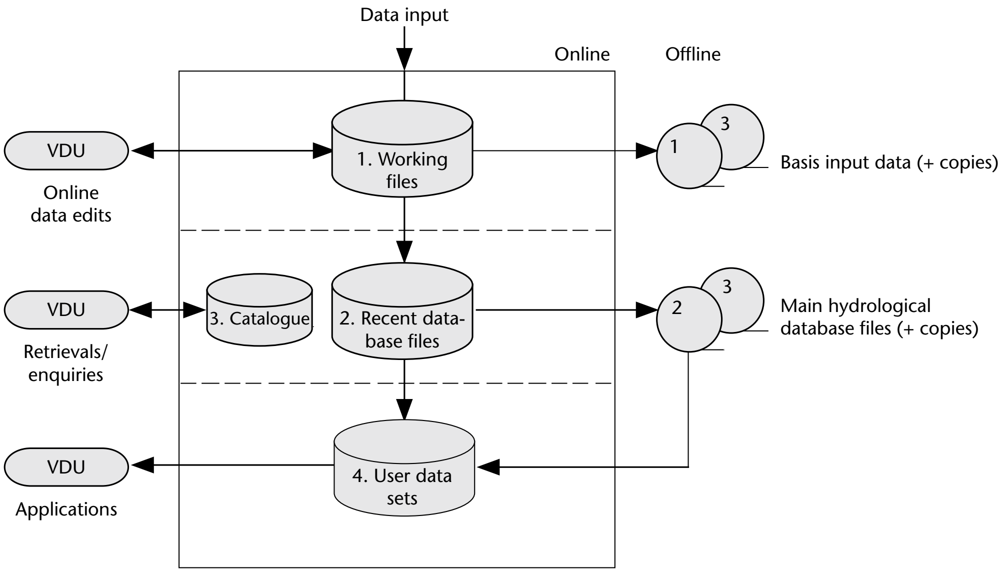


Figure I.10.4. Disposition of online and offline data sets

of recently collected data, and recently made forecasts, at the processing centre.

10.4 DATA DISSEMINATION

10.4.1 General

Data are of no value until they are used; only when hydrological data are analysed and used as part of the water management planning and decision-making process do they become really valuable. Good quality long-term records are needed in order to quantify the mean and variability (both seasonal and inter-annual) of any hydrological variable. Thus, the standard period of data required for 'reliable' estimation of mean annual rainfall is 30 years, and yet given very long observed periodicities in rainfall in some parts of the world, perhaps even this is not really sufficient. In addition, given clear evidence of global warming and associated climate change, scientists and engineers require long records to be able to detect and monitor trends in rainfall, river flows and groundwater recharge to enable the preparation of contingency plans for coping with changing water resources.

To be useful, good quality data must also be readily available to a range of users. Data are often collected by agencies that are themselves the primary users of the data, such that the data collection underpins the work of the agency, for example, public water supply, operation of irrigation schemes or operation of hydropower facilities. Such agencies are often, but not always, governmental bodies. In such cases, internal dissemination of data in the agency is a matter that will not be dealt with here. This Guide considers how potential users of the data who are not part of the collecting agency can access hydrometeorological data, assuming that the data have been entered into an appropriate database system as described earlier.

Potential external users of hydrological data might include staff of other government departments, private sector water supply or hydropower companies, engineering or environmental consultants, academics and researchers. A wide range of potential users exist, whose requirements for data are quite variable, with some needing solely data from a single point on a single river, and others requiring data over a region, whole country or even groups of countries in the case of transboundary rivers.

Access to data

International access to data, both meteorological and hydrological, is a subject that engaged the attention of the World Meteorological Organization and its Member countries over many years. This resulted in the adoption by the Twelfth WMO Congress in 1995 of Resolution 40 (Cg-XII) that sets out WMO policy and practice for the exchange of meteorological and related data and products, including guidelines on relationships in commercial meteorological activities. At its subsequent session in 1999, the Thirteenth WMO Congress adopted Resolution 25 (Cg-XIII) – Exchange of hydrological data and products – thereby establishing the policy and practice for the international exchange of hydrological data and products. This Resolution provides the framework to facilitate international access to hydrological data and products (see WMO-No. 925). The full text of Resolution 25 (Cg–XIII) is also available at: http://www.wmo.int/pages/prog/hwrp/documents/Resolution_25.pdf.

10.4.2 Catalogues of data availability

The first requirement of any user of the data will generally be maps showing the location of all stations of various types, combined with tables showing the data held at each site, and the period of record covered by each. This type of information forms the metadatabase of the data set, and may be a separate set of data tables within a computerized database (as described earlier), or may take the form of hard-copy printed material. Thus users may either access this sort of information electronically via an Internet portal, or may have to search for the material using printed yearbooks.

The traditional means of providing such information to users was through yearbooks, often printed annually, although sometimes summary catalogues of data holdings might only be produced every three to five years, as data networks are generally fairly stable over time. This approach is simple, but can be expensive in terms of printing costs, and the printed catalogues may not be easily accessible to all users. However, for many years, printed catalogues have often been the most effective means of disseminating information on data availability and will continue to be effective in countries where Internet access is not commonly, or reliably, available.

However, in the future the most common means of making such catalogue data available to users is increasingly likely to be through a web-based browser linked directly to the metadata. This has the advantage of being available to all users with Internet access, and there is no requirement to have yearbooks. It is also potentially easier to maintain the system and to keep it up to date.

For each gauged catchment, the information provided should include:

(a) Details of the catchment, for example, its size, geomorphology, landforms, vegetation and land use;
(b) Climate zone and average annual rainfall and evaporation for the catchment;
(c) Location, type and quality of the gauging station;
(d) Details of any upstream regulation or factors that may complicate the use of the records;
(e) Period, completeness and quality of the streamflow and water quality (including sediment transport) records;
(f) Locations of meteorological stations in or near the catchment and their periods of record.

This information is grouped and discussed under three headings, namely descriptive information, catchment map and data availability.

In order to assist the users in identifying the gauged catchments that are appropriate to their purposes, a description of the characteristics of each gauged catchment and the principal features of the gauging facilities, and an indication of the quality and reliability of the flow record, should be provided.

Suggested headings and pertinent information are illustrated in Table I.10.7. In practice, all details may not be available or appropriate under each heading for each gauged catchment, but it is suggested that the same format be retained throughout.

An example which complements Table I.10.7 is provided in Figure I.10.5. A map for each catchment or group of catchments has proven to be valuable. The map should be produced at a scale that is convenient for displaying the information. Catchments of different scales may warrant maps of different scales. In the near future any information for the production of catchment maps will be retained within computer-based GIS for ease of presentation at a variety of scales. The information to be included on the map is described in Table I.10.8 and a basic example is provided in Figure I.10.6.

The data-availability page should present a relatively concise and easily updated summary of streamflow, precipitation and water quality data. It should be based on monthly data for flow and precipitation and on annual water quality data. For catchments with many precipitation stations, it is impractical to include a summary for each station. All stations and their period of record are shown on the map described in the previous section, so it would be sufficient to restrict the data availability to pluviographs and a selected set of key daily precipitation stations. Stations with long periods could require several pages to ensure adequate scales for legibility.

Table I.10.7. Outline of data–catalogue format

Identification	*Description*
Name	River name, station name and station number
River basin	Basin name and number
Location	Gauging station location in latitude and longitude and local grid coordinates
Catchment details	
Catchment area	The catchment area expressed in square kilometres
Climate zones	The climate over the catchment expressed in bioclimatic zones that reflect the amount and occurrence of precipitation
Average rainfall	An assessment of the mean annual rainfall at the centroid of catchment and, for large catchments, the range of mean annual rainfall across the catchment. The sources of the figures should be quoted
Pan evaporation	An assessment of the mean annual pan evaporation at the centroid of catchment. The source of the figures should be quoted
Geomorphology	Descriptive comments on the relief, landscape and underlying geology of the gauged catchment
Landforms	Quantitative estimate of proportions of major landforms within the catchment
Natural vegetation	Descriptions of the natural vegetation derived from vegetation surveys
Clearing	Proportion of natural vegetation cleared, or substantially altered by intrusive human activity. Source and date of clearing estimates should be included.
Present vegetation	Descriptions of the present vegetation cover across the catchment with a reference to the source
Land use	Comments on land use. Source of information should be quoted, be it field observation, map of rural land use, or more detailed evaluation
Regulation	Comments on upstream developments that could modify the runoff regime. Possible sources of detailed information should be listed.
General comment	Where the station does not measure total catchment runoff or the record cannot be corrected for upstream regulation, the catchment characteristics are omitted in favour of comment on the station's particular special purposes or functions.
Gauging station details	
Period of record	Month and year of opening and closing of the gauging station. When more than one station has operated near the same river a suitable reference is included.
Classification	The gauging station's current classification within the hydrological network (for example, project station or basic-network station)
Gauging installation	Description of stage-recording instruments and the features controlling the river stage at the gauging station. Changes in either of these facilities during the period of operation should be noted.
Stage record	Annual average percentage of data recorded and percentage of these data that require interpretation in processing (faulty record)
Rating curve	Brief comments on the method and quality of the stage-discharge relationship, together with maximum measured discharge. Where possible, the proportion of measured flow that the maximum measured discharge represents should be known.
Sensitivity measure	Some measure of the rating-curve sensitivity should be provided. The preferred method to indicate sensitivity is the percentage of flow volume that could be measured to within 1, 2 or 5 per cent with a 1-mm error in the stage record. Note that this measure is based on the slope of the rating curve and the cumulative flow duration curve. Alternatively, it may be defined for a 10-mm or 100-mm error in stage.

607003 Warren River	Wheatley farm		
River basin	Warren river		
Location	Latitude S 34˚22’ 14”	AMG. Grid	N 6196500
	Longitude E 116˚16’ 34”		E50 433450
Catchment characteristics			
Catchment area	2 910 km^2		
Climate zone	Mediterranean climate; intermediate to low rainfall.		
Average rainfall	735mm/annum (Range 950–550).		
Pan evaporation	1 275 mm/annum (Range 1 250–1 400		
Geomorphology	Low to moderate relief; undulating plateau with incised mainstream valley, bauxitic laterite soils over Archean grantic and metamorphic rocks.		
Landforms	Map units; Atlas of Australian Soils (Ref. 8) 16% – Ub90 dissected laterites; rolling country with yellow mottled soils and gravelly ridges 14% – Cb43, Tf6 swampy flats; shallow drainage lines with leached sands and podzolic soils 57% – Cd22, Tc6 laterite plateau; uplands with sands and ironstone gravels over mottled clays 13% – Tf6, Ta9 incised valleys; moderate slopes. mainly yellow podzolic soils		
Natural vegetation	Map units; vegetation survey of WA (Ref. 1) 20% – eMi woodland; marri-wandoo woodlands on dissected laterites 70% – eMc forest; jarrah-marri forest on laterite plateau 10% – mLi low woodland; paperbark woods on swampy flats		
Clearing	About 40% area cleared (only 27% cleared in 1965)		
Land use	About half catchment in state forest, cleared areas used for sheep and cereal production in upper catchment and beef production in lower reaches		
Regulation	Small farm dams on minor water courses		
Gauging station details			
Period of record	May 1970 to date		
Classification	Hydrological network – primary mainstream catchment		
Gauging installation	L&S servo manometer and continuous graphical recorder to date. Rock bar control for low and medium flows; channel control for high flows		
Stage record	96.5% recorded, 7.6% faulty		
Rating curve	Low to medium rating fair due to nature of control, medium to high flow rating good, but theoretical beyond measured range. Numerous discharge measurements to 97.04m^3 s^{-1}, which represents 99% of total recorder flow yield		
Sensitivity measure	99% of flow < 1;100% of flow < 2		

Figure I.10.5. Sample data-catalogue page

Table I.10.8. Outline of map details

Identification	*Description*
Catchment boundary	Scale and source of map from which the catchment boundary was defined
Streamlines	The number of streamlines to be included should be a function of catchment area. Source of streamline data
Catchment scale	Variable – a function of catchment size
Rainfall stations	Location and station number, period of operation and type of raingauge, for instance, pluvio, daily read or storage
Rainfall isohyets (optional)	Average annual rainfall isohyets for the catchment with the reference
Land use (optional)	Where applicable the boundaries of the main land uses should be known. Forest, agricultural and urban boundaries would be one example.

It is suggested that the information in Table I.10.9 be included on the data-availability page.

10.4.3 Summary reports

Many organizations publish summaries of data. Some examples include climate averages, rainfall statistics, streamflow statistics/records and water quality records or surveys.

Typically, such publications consist of station information, including station number, latitude and longitude, type of data collected, other site specifications (name, river name, grid reference, catchment area, etc.), period of operation, period of data processed, and instantaneous, daily, monthly and annual data summaries (including minimum, maximum and mean values). Data may be presented as part of the text or attached as microfiche or provided on a computer-compatible form, such as a disk or CD-ROM.

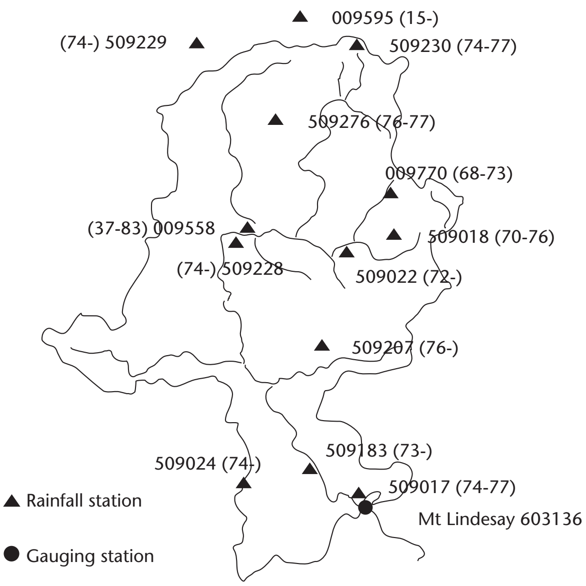


Figure I.10.6. Denmark river catchment

10.4.4 Yearbooks

A yearbook is a very effective means of disseminating hydrological data, although only certain types of data can be published. Thus, using modern data loggers or telemetry, rainfall and river levels (and hence flows) are increasingly observed every 15, 30 or 60 minutes, leading to between 8 760 and 35 040 values per year. It is neither practicable, nor generally necessary, to publish this fine time resolution data, and yearbooks generally only publish daily or even monthly rainfall totals and mean daily flows.

Groundwater data vary only slowly with time and are also sometimes monitored only intermittently, perhaps weekly or monthly. Such data sets may therefore be published in their entirety. Other climate variables, such as temperature, wind speed and radiation, are often published only as monthly means.

Examples of typical yearbook output taken from the United Kingdom National River Flow Archive (NRFA) are shown in Figures I.10.7 to I.10.13.

10.4.5 Data export on request

National hydrological data sets are increasingly being disseminated to users via the Internet, where

Table I.10.9. Outline of data-availability page(s)

Identification	*Description*
Flow data	Available record and record quality clearly presented in a month-by-month form
Rainfall data	Available record and record quality clearly presented on a month-by-month basis for the key pluviograph and manually read rainfall gauges. The period of record covered may be restricted to the period covered by the stream-gauging station for practical reasons.
Water quality	Number of samples analysed each year within a meaningful set of analyses groupings. The groupings suggested are as follows: (a) Samples with basic analysis only (any or all of conductivity, pH, river temperature, colour, or turbidity parameters); (b) Samples analysed for major icons; (c) Samples analysed for nutrients; (d) Samples analysed for heavy metals or other trace constituents.

users can use a map and tabular dialogue box interface to select stations of interest and types of data they wish to download. Internet access enables users to browse the data set and determine what types of data they require from a selected station or set of stations.

Some systems may then allow users to download the selected data directly to their own PCs, or alternatively, users may only be permitted to place an electronic request for the data onto the website. One good reason for not allowing users to download whatever data they request is that data volumes can be large, and data transfer may be unacceptably slow through some Internet service providers, particularly where slow modem links are used. For the same reason, providing the data to users in the form of attached e-mail files can be problematic given file size limitations on some e-mail portals.

Figure I.10.7. Map showing United Kingdom gauging stations held in NRFA

In many cases, the preferred option is for users requiring data to post a request on the website, with data being provided by CD, or possibly by being placed onto a File Transfer Protocol (FTP) site. The user would then be able to download the data from this site.

Data may be freely available from the website, particularly where the user is able to download data directly. However, in some cases, users may have to pay a handling charge for the data to cover the staff costs associated with preparing the CD. Although some users may object to paying for data, charging is often justified as the data-providing agency often has to justify its continued existence to its funders and managers. The fact that users are paying for data can provide at least part of an agency's funding needs, but perhaps more importantly, it demonstrates that its work is valued by external users or customers.

A good example of a web-based data retrieval system is the United Kingdom National Water Archive: http://www.nwl.ac.uk/ih/nwa/index.htm, or the website for hydrological data of USGS: http://waterdata.usgs.gov/nwis/, or as an example of data from WHYCOS projects: http://medhycos.mpl.ird.fr/ and http://aochycos.ird.ne/HTMLF/ETUDES/HYDRO/INDEX.HTM.

039002 1996 Thames at Days Weir

Measuring authority: EA	Grid reference: 41 (SU) 568 935	Catchment area (sq km): 3 444.7
First year: 1938	Level stn. (m OD): 45.80	Max. alt (m OD): 330

Daily mean gauged discharges (cubic metres per second)

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	56.600	25.800	42.600	24.800	20.400	11.000	5.380	3.970	3.730	4.120	3.520	10.000
2	57.500	24.200	40.400	21.800	23.200	8.850	5.490	3.710	3.050	3.960	4.020	9.970
3	60.600	24.200	39.100	21.100	19.300	9.250	5.320	3.640	2.770	3.550	4.060	11.100
4	56.300	22.600	38.600	20.800	13.100	9.160	5.140	3.630	2.700	2.860	7.280	12.600
5	54.700	22.400	37.700	21.100	13.900	9.130	5.170	3.430	3.120	3.090	6.880	15.400
6	54.900	24.000	33.800	20.800	15.500	8.860	6.050	3.200	3.100	3.060	8.280	13.500
7	63.400	24.000	33.700	20.500	15.500	10.100	5.640	3.060	3.060	3.040	5.620	11.200
8	77.900	23.600	33.500	20.100	16.400	14.600	5.040	2.750	2.980	3.300	5.350	9.310
9	101.000	30.700	35.000	20.100	15.500	11.800	5.270	2.760	2.970	4.110	6.450	9.320
10	109.000	53.600	35.900	21.500	14.200	11.200	5.410	3.720	2.880	3.250	5.810	8.870
11	97.600	57.200	33.300	22.500	14.100	9.190	3.870	4.850	2.990	2.980	3.210	8.810
12	84.100	81.600	34.600	22.500	14.200	8.880	5.500	4.320	3.220	3.520	4.470	8.840
13	77.800	99.800	36.000	48.400	14.100	8.410	4.730	4.220	3.250	3.430	5.480	8.340
14	69.400	90.200	35.200	40.600	13.800	7.440	3.870	3.790	3.020	3.130	4.590	8.140
15	59.300	64.100	32.000	31.500	13.900	5.880	3.940	3.680	2.940	3.170	4.340	8.500
16	54.800	53.900	31.100	26.400	13.300	6.240	3.810	3.380	2.840	3.220	5.240	8.020
17	50.400	48.400	30.600	24.700	13.200	6.020	3.820	3.340	3.180	3.420	6.390	8.430
18	46.500	48.400	25.500	21.100	13.200	5.980	3.700	2.850	2.500	4.2900	5.900	8.020
19	45.600	47.700	27.300	23.900	14.100	5.990	2.650	2.840	2.620	4.030	10.700	10.500
20	44.300	40.700	26.700	24.400	13.900	5.970	3.210	2.940	2.910	3.210	11.600	12.900
21	41.100	38.500	26.800	23.500	13.900	5.930	3.720	3.170	2.900	3.680	11.400	15.000
22	37.400	37.100	27.800	25.200	13.400	6.130	3.350	3.340	2.850	3.500	10.700	14.300
23	37.900	37.200	33.900	35.100	14.000	5.990	3.260	5.340	2.850	3.380	9.080	12.100
24	38.400	59.000	36.400	42.800	19.500	5.660	3.210	6.820	3.150	3.410	8.330	10.100
25	37.600	95.400	32.500	26.800	15.300	5.510	3.200	7.110	3.660	3.010	11.900	10.700
26	33.700	92.500	34.200	25.000	15.700	5.480	3.270	4.790	3.750	3.530	11.900	10.100
27	32.900	73.700	45.900	22.000	13.100	4.660	3.430	3.800	3.300	4.120	12.600	9.530
28	26.800	59.100	33.300	21.700	12.800	4.970	4.000	3.960	3.340	3.870	10.300	8.340
29	26.500	43.600	32.300	20.600	12.800	5.570	5.480	3.210	3.370	4.670	10.100	8.720
30	26.300		26.300	20.500	11.100	5.520	4.620	3.590	3.350	4.560	9.390	9.030
31	26.100		25.500		11.000		3.950	4.180		3.240		8.830
Average	54.400	49.750	33.470	25.390	14.750	7.646	4.339	3.851	3.078	3.539	7.496	10.270
Lowest	26.100	22.400	25.500	20.100	11.000	4.660	2.650	2.750	2.500	2.860	3.210	8.020
Highest	109.000	99.800	45.900	48.400	23.200	14.600	6.050	7.110	3.750	4.670	12.600	15.400
Monthly total (million cu m)	145.70	124.70	89.64	65.82	39.52	19.82	11.62	10.32	7.98	9.48	19.43	27.52
Runoff (mm)	42	36	26	19	11	6	3	3	2	3	6	8
Rainfall (mm)	42	63	36	49	36	21	34	53	22	50	79	29

Statistics of monthly data for previous record (October 1938 to December 1995)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean flows	Avg.	56.450	56.680	44.600	30.650	20.140	14.260	8.397	7.073	8.666	14.960	30.750	45.570
	Low	6.252	5.548	5.619	4.255	2.854	1.504	0.401	0.290	1.740	2.782	3.751	5.308
	(year)	1976	1976	1976	1976	1976	1976	1976	1976	1959	1959	1990	1975
	High	133.600	120.800	163.200	85.060	61.140	41.560	48.810	18.690	38.640	74.570	128.100	128.700
	(year)	1939	1977	1947	1951	1983	1955	1968	1977	1946	1960	1960	1960
Runoff	Avg.	44	40	35	23	16	11	7	5	7	12	23	35
	Low	5	4	4	3	2	1	0	0	1	2	3	4
	High	104	85	127	64	48	31	38	15	29	58	96	100
Rainfall	Avg.	68	47	53	47	58	54	53	64	62	64	70	73
	Low	13	3	5	4	7	5	5	3	5	6	8	16
	High	132	135	152	99	131	124	117	149	129	163	178	316

Summary statistics

	For 1996		For record preceding 1996		1996 As % of pre-1996
Mean flow	18.070		28.050		64
Lowest yearly mean			10.100	1973	
Highest yearly mean			51.290	1960	
Lowest monthly mean	3.078	Sep	0.290	Aug 1976	
Highest monthly mean	54.400	Jan	163.200	Mar 1947	
Lowest daily mean	2.500	18 Sep	0.050	7 Jul 1976	
Highest daily mean	109.000	10 Jan	349.000	17 Mar 1947	
10% exceedance	44.770		67.810		66
50% exceedance	9.412		15.940		59
95% exceedance	2.959		3.181		93
Annual total (million cu m)	571.40		885.20		65
Annual runoff (mm)	166		257		65
Annual rainfall (mm)	514		713		72
{1961–1990 rainfall average (mm)			690}		

Factors affecting runoff

$ Abstraction for public water supplies
$ Flow reduced by industrial and/or agricultural abstractions
$ Augmentation from effluent returns

Figure I.10.8. Example of NRFA yearbook tabulations

39002 – Thames at Days Weir

Grid reference	41 (SU) 568 935
Operator	EA
Local number	1900
Catchment area	3 444.7 km^2
Level of station	45.8 m OD
Maximum altitude	330.0 m OD
Mean flow	28.38 m^3 s^{-1}
95% exceedance (Q95)	3.22 m^3 s^{-1}
10% exceedance (Q10)	69.2 m^3 s^{-1}
1961–1990 average annual rainfall	690 mm

Figure I.10.9. Station characteristics

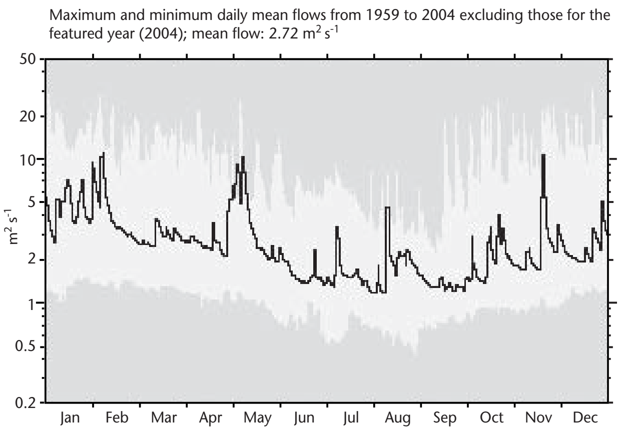


Figure I.10.10. Sample hydrograph of gauged daily flows

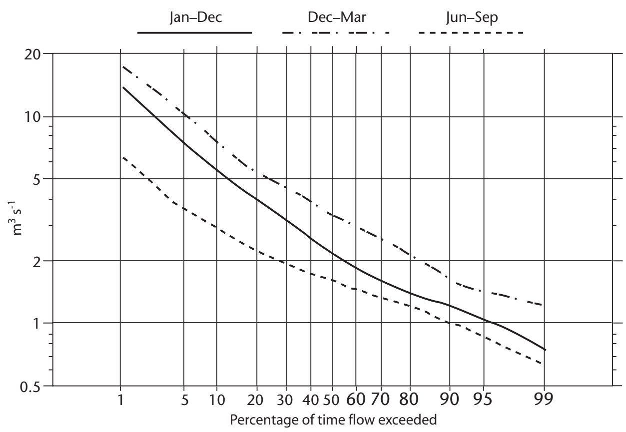


Figure I.10.11. Flow duration curve for gauged daily flows

Station description

Adjustable thin-plate weir (5.48 m wide) plus 15 radial gates, replaced a barrage of radial and buck gates in 1969. Rating formulae based on gaugings – tailwater calibration applies for flows > 70 cumecs; above 100 cumecs overspill occurs. Daily naturalized flows available for POR (equal to gauged flows up to 1973) – allow for Didcot power station losses only. Peak flows under review.

Catchment description

Mixed geology (oolitic limestone headwaters, oxford clay below). Predominately rural with development concentrated along the valley.

Factors affecting runoff

- Runoff reduced by public water supply abstraction
- Runoff increased by effluent returns
- Runoff reduced by industrial/agricultural abstraction

Figure I.10.12. Example of metadata

10.4.6 Data-exchange formats

There are currently no standards for data exchange formats for hydrological data. The only standards that exist are the de facto standard formats produced by the most common data loggers and database software systems. Current data exchange formats generally fall into two categories, as follows.

Text-based files

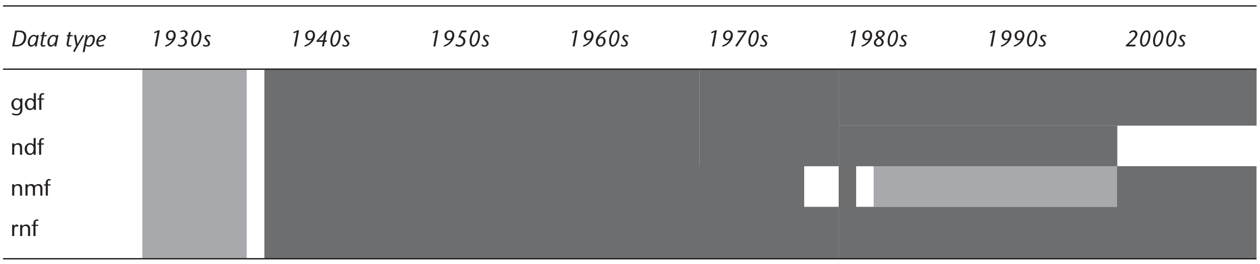
Text-based data files have the benefit of being easily readable by a user with the simplest of computer software. Data time series are often stored as columns of dates, times and values, with each value separated by a delimiter that could be a comma (resulting in a comma-separated value, or CSV, file), or other character or fixed number of spaces.

Proprietary format

The disadvantage of text-based formats is the size of the resulting file. Many software systems use proprietary formats that make far more efficient use of memory. This results in smaller files that take up less space on computer disks or transfer media and are faster to move around the Internet. The disadvantage is, of course, that specialist software is usually required in order to read the files.

XML

There is a movement towards data exchange format identification with the widespread uptake of XML, which stands for Extensible Markup Language (Word Wide Web Consortium, 2004). XML is itself a standardized format for data files, albeit at the most general level. With the increasing use of the Internet during the 1990s, particularly in the areas of publishing, manufacturing and retail, there was a need for a standard way for computer programs to be able to read data files and make sense of the content, without prior knowledge of the format. In 1998, XML was defined by the World Wide Web Consortium (W3C) as a platform and method for putting structured data into a text file. XML is similar to HyperText Markup Language (HTML), the most common format for files on the Internet, which allows many different software packages to display the content of files of this format in the same way. But whereas HTML describes how the content should look, XML says nothing about presentation and simply describes what the content is.



Gauged daily flows (gdf): 1938 to 2003
Naturalized daily flows (ndf): 1938 to 2002
Naturalized monthly flows (nmf): 1938 to 2002
Monthly catchment rainfall (rnf): 1938 to 2001

Figure I.10.13. River flow and catchment rainfall in NRFA

Table I.10.10. Gauging station's name and coordinates in XML

```
<gaugingstation>
    <name>River Thames at Wallingford
    </name>
    <coordinates>
        <easting unit=metres>461300
        </easting>
        <northing unit=metres>189900
        </northing>
    </coordinates>
</gaugingstation>
```

The content of the data file is written within tags, which describe what the data are about. For example, Table I.10.10 contains a gauging station's name and coordinates in XML.

A computer program reading this XML would know, without understanding anything about hydrology, that the file contains information about a 'gauging-station', that it has an attribute called 'name' that this attribute has a value 'River Thames at Wallingford', and that it has 'coordinates' with further attributes 'easting' of value 461300 and 'northing' with value 189900, both with units of 'metres'. The '<>' symbols are called tags, and pairs of tags enclose data values, while the text within the tags describes the data enclosed.

The advantages and disadvantages of XML are widely discussed, but can be summarized simply.

Advantages: Ability to separate form from content, and thus quickly apply different rules of display to a range of files of the same format. The data that can be stored in a file, as well as rules for these data, can be explicitly stated and software can use this to validate data files whilst reading. Files can be also searched efficiently.

Disadvantages: The uncompressed text file means that file sizes are large. XML was not invented for the purpose of describing time-series data that can increase file sizes by a factor of 10 over even uncompressed text-based formats.

One major advantage of XML is that it can be specialized in particular subjects. For example, libraries have defined an international format for describing the tags and rules for storing information about books in XML. These standards indicate that all libraries can provide data that can be read and understood by all other libraries. The same is gradually occurring in the more complex area of environmental science. Already there are emerging XML formats for a wide range of applications, including the description of molecules and the Climate Science Modelling Language. GIS data now have a comprehensive XML-based standard called the Geography Markup Language (GML) that will allow the interaction of digital maps from all sources, and could be used for the dissemination of spatial data. GML is the XML grammar defined by the Open Geospatial Consortium (OGC) to express geographical features (Cox and others, 2004). GML serves as a modelling language for geographic systems as well as an open interchange format for geographic transactions on the Internet.

Many of the definitions of these XML specialisms (areas in which XML specializes) are still evolving and thus should be used with care. However, some successfully defined languages have achieved ISO standard recognition. An XML specialization in the field of hydrology has not yet been developed, although the United States National Weather Service has established a Hydrology XML consortium and produced a draft hydrology XML schema.

References and further reading

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ANNEX

ABBREVIATIONS AND ACRONYMS

2D	Two-dimensional
ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
ADVM	Acoustic Doppler Velocity Meter
AVHRR	Advanced Very High Resolution Radiometer
BOD	Biochemical Oxygen Demand
DBMS	Database management systems
DMSP	Defense Meteorological Satellite Program
EDI	Equal Discharge Increment
EMS	Electromagnetic spectrum
EOS	Earth Observation Satellites
ERS	European remote-sensing satellite
ET	Evapotranspiration
ETR	Equal transit rate
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FAO	Food and Agriculture Organization of the United Nations
FDR	Frequency domain reflectrometry
GEMS	Global Environment Monitoring System
GIS	Geographical Information System
GOES	Geostationary Operational Environmental Satellite
GPCP	Global Precipitation Climatology Project
GPI	Global Precipitation Index
HOMS	Hydrological Operational Multipurpose System
HTML	HyperText Markup Language
IAEA	International Atomic Energy Agency
IAHS	International Association of Hydrological Sciences
ICWE	International Conference on Water and the Environment
IGBP	International Geosphere-Biosphere Programme
IR	Infra-red
ISO	International Organization for Standardization
IT	Information technology
MODIS	Moderate Resolution Imaging Spectroradiometer
MSS	Multispectral Scanner
NAQUADAT	Canadian National Water Quality Data Bank
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmosphere Administration
NRFA	National River Flow Archive (United Kingdom)
RDBMS	Relational Database Management Systems
SAR	Synthetic Aperture Radar
SPOT	Satellites pour l'observation de la terre
SSM/I	Special Sensor Microwave/Imager
TDR	Time domain reflectrometry
TIDEDA	Time Dependent Data (New Zealand)
TIRO	Television infrared observation satellite
TRMM	Tropical Rainfall Measurement Mission
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
VPR	Vertical Profile of Reflectivity
WATSTORE	Water Data Storage and Retrieval
WHO	World Health Organization
WMO	World Meteorological Organization
XML	Extensible Markup Language

www.wmo.int