TECHNICAL
REPORT SERIES
No. 2

TECHNICAL MATERIAL FOR WATER RESOURCES ASSESSMENT

World
Meteorological
Organization
Weather • Climate • Water

WMO-No. 1095

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CONTENTS

PREFACE

The aim of the present publication is to provide technical material in a reasonably logical progression as required for carrying out a water resources assessment (WRA).

The technical material contained in the present publication was collected over the time span covering two intersessional periods of the WMO Commission for Hydrology. Therefore, a number of people were responsible for the oversight of the collection, review and editing of the material. The two members of the Commission for Hydrology Advisory Working Group with the greatest level of involvement in the publication during that period were Dr Ann Calver and Dr Jeanna Balonishnikova, each, at some stage, with responsibility for the water resources assessment thematic area of the work of the Commission.

The list of contributors is extensive and, while every effort has been made to include the names of those who have contributed, we inadvertently may have omitted some names. If your name is not included below and you have contributed to the material in the present publication, please accept both our appreciation for your efforts and our apologies for the omission. Please let us know so that we can make adjustments to the publication for future releases.

Contributions to the present publication have been made by the following:

O. Anisimov, J. Bolonishnikova, A. Calver, F. Farquharson, A. Lipponen, B.O. Mahykano, A.M.J. Meijerink, A. Oke, J.N. Okpara, D. Richardson, L. Shelley, Y. Strelchenko, S. Vasak, S. Vermooten and J. Vrba. Organizations that have also contributed include the United Nations Economic Commission for Europe (UNECE) and the United Nations Educational, Scientific and Cultural Organization (UNESCO).

WMO extends it appreciation to all those who have contributed to the material contained in the present publication.

For a glossary of the terms used in the present publication, the reader is referred to the *International Glossary of Hydrology* (WMO/UNESCO, 2010).

CHAPTER 1. INTRODUCTION

1.1 PURPOSE OF THE TECHNICAL MATERIAL

An ability to assess the availability of freshwater (water) resources has been an issue of importance in most countries for many decades. A number of guidelines and manuals have been produced offering advice to staff of National Hydrological Services (NHSs) or water agencies on how to quantify their water resources (World Bank, 1994; WMO/UNESCO, 1991, 1997; UNESCO, 1998). Some of this guidance is now out of date, particularly given recent developments in topographic mapping, through availability of digital terrain models, because of advances in computerized geographical information systems (GIS), and with increasing availability of high-resolution remotely sensed data. In addition, the Internet now provides users with a wealth of new datasets that can be of considerable value. There is therefore a need to update previous material, and to provide staff of regional or national agencies with improved guidance on how to reliably quantify their sustainable long-term water resources. Water resources assessment is a national responsibility that requires special arrangements and capabilities in the country to enable an appropriate assessment. In this regard, WMO and UNESCO produced the *Water Resources – Handbook for Review of National Capabilities* (WMO/UNESCO, 1997) and held a range of workshops to introduce the methodology described in the Handbook. The technical material contained herein expands on and gives further guidance to the material provided in the Handbook.

The present technical material is aimed primarily at staff of agencies working in the water sector, including NHSs, water resources managers, water suppliers and water users responsible for quantifying available surface water and groundwater resources. However, this material should be of value to all those carrying out or commissioning such assessments. The material contained herein is intended to be fairly comprehensive, and the publication self-contained, although frequent references are given to other sources of supporting material, much of it available from the Internet. Whilst it is recognized that not all potential users will yet have full or reliable access to the power of the Internet, it is assumed that access for the target group is likely to improve over time.

1.2 PERCEIVED NEEDS FOR THE TECHNICAL MATERIAL

Water is vital to all forms of life on Earth, from plants and the simplest of organisms through to animals and humankind. Lack of access to fresh drinking water is one of the prime constraints to health and development in many countries. Water is a vital input to agriculture and a lack of adequate water for irrigation and livestock is also often a constraint on human development. Disappointingly, access to a safe water supply is not explicitly included as one of the eight United Nations Millennium Development Goals, although indirectly it does have an impact on the following Goals: 1 – Eradicate extreme poverty and hunger, 4 – Reduce child mortality, 5 – Improve maternal health, 6– Combat HIV/AIDS, malaria and other diseases, and 7 – Ensure environmental sustainability, where a sub-aim is to reduce by half the proportion of people without sustainable access to safe drinking water.

Assessment of water resources at the basin, regional or national scales has been undertaken on many occasions in many countries of the world. Often, however, such assessments have not always been as effective as they might have been and have been constrained by a lack of sufficient good quality data. Good quality, long-term records of climate (particularly precipitation), river flows, reservoir levels and groundwater levels are vital to ensure that current assessments of available freshwater resources are accurate. Unfortunately, in many parts of the world, national decision-makers and ministries of finance consistently have failed to appreciate the importance of maintaining long-term, good quality environmental records. Throughout much of Africa in particular, there is marked annual variability in both precipitation inputs and in resulting river flows, lake storages and groundwater levels (Servat et al., 1998). Thus, even an apparently adequate 20- to 30-year record may not be able to define accurately the true historical mean and variability of resources. In addition, it is now clear that the world is, in places, experiencing trends in key climatic parameters, such as temperature and precipitation, as well as the continuation of natural variability. Thus records of past water resources may no longer be the most reliable indicator of future supplies, but will continue to provide valuable information on trends and variability. There is therefore a pressing need for new scenario-based approaches to future resource modelling and continuing, reliable long-term records to determine trends in water availability under a changing climate.

Following the organization of workshops on the *Water Resources – Handbook for Review of National Capabilities* (WMO/UNESCO, 1997), it was realized that there was a need for further technical material to be provided for water resources assessment, focusing more on how such analyses should be carried out.

1.3 OBJECTIVES AND TARGET GROUPS/BENEFICIARIES OF THE TECHNICAL MATERIAL

This technical material is intended as a “subsidiary” tool for operational staff in agencies responsible for quantifying natural water resources at the national, basin or regional (both subnational and supranational) scale. The material will concentrate on determining the absolute quantity of elements of water balance that are needed for water resources assessment. Thus the information provided will stop short of water resources development and management. The material is intended as an aid to quantifying water resources, but will not consider how these resources should be developed or managed operationally.

Whilst the technical material is perhaps more likely to be used by NHSs in less developed countries, where access to other international literature is often limited, the principles are designed to have general application and be applicable in all regions of the world. The information provided should be of use not only to technically qualified staff in relevant government agencies and their consultants undertaking studies, but also to those managing programmes of work and specifying, managing and reviewing studies carried out by specialist consultants.

This technical material aims to provide clear directions for national experts within a single volume. Although much of the material presented may be available in textbooks, including the sixth edition of the WMO *Guide to Hydrological Practices* (WMO, 2008*a*), neither current textbooks nor the Guide contain the practical guidance in a compact form. Other publications, such as the UNESCO *Hydrology and Water Resources of Small Islands: A Practical Guide* (UNESCO, 1991) and the UNESCO *Water Resources Assessment – Integral Water Balance in Basins* (UNESCO, 2008), focus on particular geographical locations whereas the material contained herein attempts to cover all geographical locations. Publications such as the UNESCO *Methods for Water Balance Computations – An International Guide for Research and Practice* (UNESCO, 1974) have a research focus and are in some cases dated. Thus, even where similar information is available from other published sources, users would have to skip from chapter to chapter within the *Guide to Hydrological Practices* or read through a wide range of textbooks to find the material needed.

1.4 LINKS TO OTHER PROGRAMMES

The topics in this guidance material have clear links to a number of international, national and subnational programmes. The WMO-related programmes include the following:

- The Global Runoff Data Centre has collated runoff data from over 150 countries, facilitates the exchange of hydrological data and promotes research on climate change and Integrated Water Resources Management (IWRM).
  http://www.bafg.de/GRDC/EN/Home/homepage__node.html

- The Hydrological Operational Multipurpose System (HOMS) promotes the transfer of technology in hydrology and water resources.
  http://www.wmo.int/pages/prog/hwrp/homs/homs_en.html

- The World Hydrological Cycle Observing System (WHYCOS) is aimed at improving basic observation activities, strengthening international cooperation and promoting free exchange of hydrological data.
  http://www.whycos.org/rubrique.php3?id_rubrique=2

- The Global Terrestrial Network – Hydrology (GTN-H) links existing networks and systems for integrated observations of the global water cycle.
  http://gtn-h.unh.edu/

There are also links to other international programmes, including the following:

- The UNESCO Water Portal promotes access to Web-based information on freshwater.
  http://www.unesco.org/water/

- The World Water Assessment Programme monitors freshwater issues in order to provide recommendations, develop case studies, enhance assessment capacity at a national level and inform the decision-making process. Its primary product, the World Water Development Report (WWDR), is a periodic, comprehensive review providing an authoritative picture of the state of the world's freshwater resources.
  http://www.unesco.org/water/wwap/

- The Global Water System Project promotes the coordination of integrated research on water and related human impacts.
  http://www.gwsp.org/

- The United Nations Environment Programme (UNEP) Global International Waters Assessment prepared a comprehensive and integrated assessment of waters in different global regions.
  http://www.unep.org/dewa/giwa/

Appendices I through IX of WMO/UNESCO (1997) provide additional details and background on links to other international, regional and national activities.

http://www.wmo.int/pages/prog/hwrp/documents/english/handbook.pdf

1.5 LINKS TO SUSTAINABLE DEVELOPMENT AND INTEGRATED WATER RESOURCES MANAGEMENT

At the World Summit on Sustainable Development, held in Johannesburg, South Africa, in 2002, the international community took an important step towards more sustainable patterns of water management by including, in the Plan of Implementation of the World Summit on Sustainable Development, a call for all countries to develop IWRM and water efficiency plans. Integrated Water Resources Management recognizes that water must be managed to meet many simultaneous needs, that several sectors (agencies) with legitimate interest in water must work together, and that the complexities of the hydrological cycle require a integrated approach to make best use of the water available. It is commonly taken to include or be linked with the management of soil, vegetation and land use. It emphasizes river basin as the logical unit for planning water resources management. Achieving IWRM as part of a broader approach to sustainable development is a major challenge for all regions and countries, particularly in the face of economic, social and ecological problems.

There is now wide acceptance of the aim that all development, including water resources development, must be sustainable, which implies that the world's natural resources must be managed and conserved in such a way as to meet the needs for present and future generations (WMO, 2008*a*).

Clearly a starting point for the ambitious goals of IWRM and sustainable development is to have a good understanding of underlying water availability, now and in the future, and this is the aim of water resources assessment. This fundamental principal has been reaffirmed at the six World Water Forums held over the past fifteen years and in particular in the Ministerial Declaration of the 6th World Water Forum, held in Marseilles, France, in March 2012.

1.6 THE ECONOMIC JUSTIFICATION FOR WATER RESOURCES ASSESSMENT

Accurate information on the condition and trend of a country's water resources – surface water and groundwater, quantity and quality – is required to support sustainable economic and social development whilst addressing maintenance of environmental quality. Uses of water resources information are many and varied. Almost every sector of a nation's economy uses water information for planning, development or operational purposes. As a basic necessity water is often difficult to value in absolute economic terms, but in all countries as competition for water increases, water information grows in value. Because the cost of government programmes must be properly justified, it is becoming very important to demonstrate the benefits of hydrological information and analysis. Benefit-to-cost ratios for hydrological data collection of up to 40:1 have been cited (that is, the value of the information is forty times its cost of collection). Benefit-cost ratios in the range 5 to 10 seem to be generally plausible, with values of 9.3 and 6.4 being found in studies in Canada (Acres Consulting Services Limited, 1977) and Australia (Cordery and Cloke, 1992; Wain et al., 1992), respectively. Regardless of the actual numerical values, water managers in all countries and at all levels subscribe to the view that good quality hydrological information is an essential prerequisite for wise decision-making in water resources management. Clearly when drawing up programmes for water resources assessment, which are often publicly funded, it is important to relate the cost (and therefore the scope and extent) of modelling and analysis to the benefits that are likely to be realized by the wider community.

The International Conference on Secure and Sustainable Living: Social and Economic Benefits of Weather, Climate and Water Services organized by WMO, took place in Madrid, from 19 to 22 March 2007. The purpose of the Conference was to contribute to secure and sustainable living for all the peoples of the world by evaluating and demonstrating, and thence ultimately enhancing, the social and economic benefits of weather, climate and water services. It sought to assemble authoritative feedback from the users of these services in order to, inter alia:

(a) Inform governments and stakeholders in general of the immense societal benefits at the national and local levels that flow from their investment in the meteorological and hydrological infrastructure that supports the provision of meteorological and related services at the national level in every country;

(b) Initiate and promote new approaches, in the research, education and applications communities, to evaluation of the social and economic benefits of meteorological and related services;

(c) Guide the priorities of the National Meteorological and Hydrological Services for infrastructure investment, service provision and service delivery.

The Conference report continues a long line of publications prepared by WMO and others on economic benefits of National Hydrological Services (WMO, 1994, 1995, 2007; Freebairn and Zillman, 2002).

1.7 STRUCTURE OF THE TECHNICAL MATERIAL

The technical material consists of 11 chapters, a bibliography, and related appendices.

The general principles are discussed in Chapter 2, followed by considerations for the review of existing information in Chapter 3 and a detailed discussion of the collection, processing and archiving of different sources of data in Chapter 4. Chapters 5 to 8 then focus on different aspects of hydrometeorological analysis – precipitation in Chapter 5, evaporation in Chapter 6, surface water in Chapter 7 and groundwater in Chapter 8. Chapter 9 then covers the assessment of total water availability and Chapter 10 discusses the range of impacts on water resources. Lastly, Chapter 11 discusses the presentation of results of water resources assessment activities.

CHAPTER 2. WATER RESOURCES ASSESSMENT

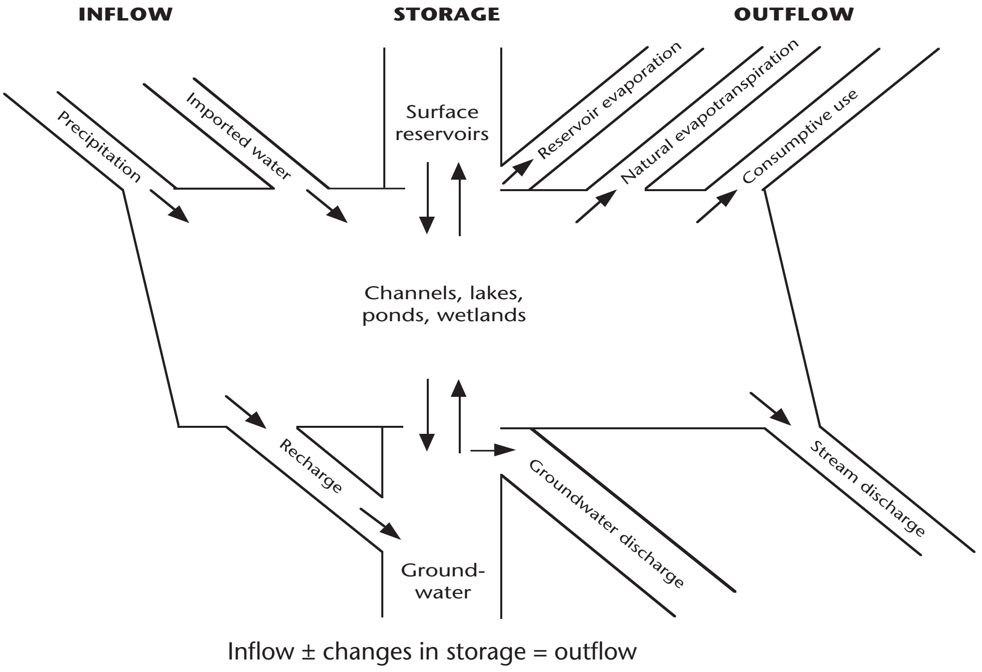
2.1 GENERAL APPROACH

Water resources assessment relies on a full understanding of all the water flows and storages in the river basin or catchment under consideration. A diagrammatic representation of the main flows and stores in a typical sub-humid catchment is shown in Figure 2.1. It will be broadly applicable to a wide range of river basins and can readily be adapted to other situations. For example, in mountainous and high latitude areas there will be a significant element of storage in snow fields and glaciers and in the driest river basins long-term groundwater storage will predominate and nighttime surface condensation may be a measurable additional source.

The process of water resources assessment involves developing as complete an understanding as possible of these flows and stores and their interrelationship over time. Only then is it possible to estimate what sustainable surplus flows may be made available for human or other uses as both sources and systems change in the future through climate change, natural evolution or human-made interventions.

2.2 SCALES OF WATER RESOURCES ASSESSMENT

In general, an acceptable water resources assessment requires clear hydrological boundaries across which both surface water and groundwater flows can either be measured with reasonable confidence or effectively assumed to be zero. For a river basin, the broadest scale of assessment will be from the watershed with adjacent river basins to the outlet to the sea. However, for many purposes, assessments will be conducted on smaller sub-basin areas. In any case, care is always needed in defining watershed boundaries, particularly in geological formations where groundwater flows are significant, as the extent of aquifers does not necessarily correspond with basin boundaries.



Source: Guide to Hydrological Practices (WMO-No. 168), fifth edition, page 27

Figure 2.1. Diagram showing major elements of a hydrological system needed for a water budget of a typical river basin in a sub-humid region

Where several countries share a river basin, it is very important that joint working relationships are established to promote discussion on the best ways to manage water resources overall. This is required so that actions of upstream States do not prejudice the reasonable rights of those downstream. Such collaboration relationships include River Basin Authorities and River Basin Commissions.

However, there will also be times when water resources need to be assessed and reported on in terms of administrative boundaries. Therefore there are a number of scales, including river watersheds, groundwater systems, transboundary territories and administrative territories (local, state, national), on which water resources assessments could be made.

2.3 DEFINITION OF TERMS

Water resources assessment is the determination of the sources, extent, dependability and quality of water resources for their utilization and control, and water resources are the water available, or capable of being made available, for use in sufficient quantity and quality at a location and over a period of time appropriate for an identifiable demand.

The term sustainable development was coined in the paper "Our Common Future" that was released by the Brundtland Commission (United Nations, 1987). Sustainable development is the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development in the management of water resources implies that future generations, as well as the present one, will continue to enjoy adequate and available water supplies to meet their social, environmental and economic needs.

A full glossary of terms related to this technical material can be obtained from the *International Glossary of Hydrology* (WMO/UNESCO, 2010).

2.4 STEPS IN WATER RESOURCES ASSESSMENT

The key steps in carrying out the water resources development process are illustrated in Figure 2.2.

The first stage in any WRA should be a high-level review of the catchment to determine which of the processes in Figure 2.1 are dominant and therefore where subsequent investigations should be targeted. This preliminary assessment should, of course, be reviewed and revisited during the process to check that initial assumptions are still valid in the light of data gathered and analyses undertaken.

The next stage is a comprehensive gathering and collation of recent and historical hydrological data related to the target area (for example, catchment, river basin, groundwater system). This will include data on precipitation, evaporation, river flow, surface storage, soil moisture and groundwater and, where relevant, snow fields and glaciers (see section 4.3).

Along with this, comprehensive information on the physiographic features of the basin should be collated and mapped in compatible systems together with relevant socio-economic and water-use data (see sections 4.2 to 4.5).

Having assembled all the data, the next stage is analysis to understand the key interactions in the catchment and confirm the key features of both short-term and long-term water balances. In most cases this will result in the construction of some form of model, which might be a relatively simple monthly water balance model but might be a much more complex model that aims to reproduce many of the major water transfers within the catchment.

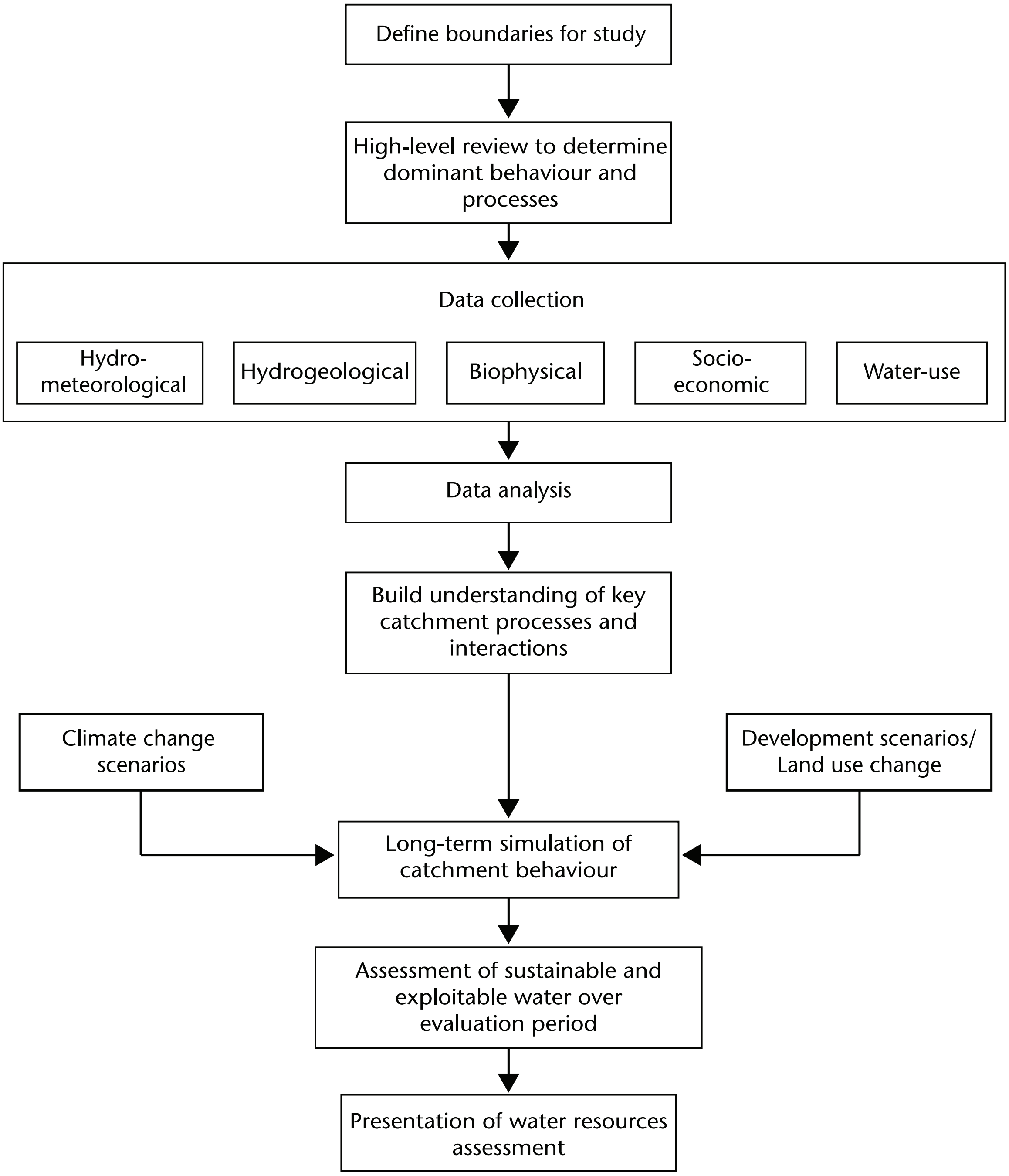


Figure 2.2. Outline schematic of the water resources assessment development process

The choice, development and validation of such models require considerable judgement and experience, and the more complex models are extremely difficult to validate with any confidence even where very detailed long-term datasets are available. Any analysis of the data, including modelling, will need to address issues of the seasonality of flow and the natural variability that occurs from year to year. It is this inherent natural variability that is the essential ingredient to understanding water availability and thus to water resources management.

An important aspect of the analysis phase is the consideration of water quality and environmental issues. Contamination of water sources, whether by natural or human-induced pollutants, can significantly affect the resources available for effective use and so must be factored into resource assessments. The quality of groundwater also varies. In addition, it is increasingly recognized that there are minimum flow regimes required to support and maintain many valuable aquatic habitats that are important for the support of both animal and human populations, for example, fish spawning. These are often referred to as environmental allocations or environmental flows. These must also be factored into any analysis of water availability.

Having established the way that the catchment behaves and its key interactions through process analysis, this understanding can then be used to examine the performance of the basin in water resources terms by applying long-term time series of synthesized input data. By synthesizing long-term records based on current climate, it is possible to determine credible statistics such as return periods and probabilities, for example, for different drought durations and frequencies even if the actual input sequences which would cause them have not actually occurred in the period of record. These long input sequences can then be adjusted, using the best knowledge of the way in which climate and other factors might change in the future, to examine all aspects of water resources sensitivity to future change.

Following this analysis, an important stage is the presentation of results to relevant professional and lay audiences. The presentation of future projections and realistic bands of uncertainty will be a particular challenge (see Chapter 11).

2.5 INFORMATION NEEDS

It follows from the above that key types of data required include the following:

(a) Biophysical data – topography, soils, geology and vegetation – required for modelling and to set the environmental constraints;

(b) Hydrometeorological data – characteristics of climate, surface water and groundwater – required to define the available resource characteristics;

(c) Socio-economic data – land use and demography – required for understanding the water needs;

(d) Water-use data – required to complete the picture of supply–demand.

Each of these data categories is considered in Chapter 4 after a general discussion of data and information in Chapter 3. In addition, climate projections and changes in the catchment and in water demand need to be considered as the basis for long-term future simulation (see Chapter 10).

CHAPTER 3. REVIEWING EXISTING INFORMATION

3.1 INTRODUCTION AND CONCEPTS

Information is the backbone of any water resources assessment. The specific types of information and data required in WRA are considered in detail in Chapter 4. Acquisition of water-related data is costly and time-consuming. Field expeditions, drilling of boreholes, design, installation and maintenance of monitoring networks and other data collection schemes require large investments and long-term logistics. To minimize these costs and time-consuming activities it is essential to first review the existing information related to the studied area. This is an essential part of any water resources assessment and can save a lot of money, time and effort.

Historically, collected data correspond to values measured at a specific time, which makes them of great importance when investigating the variations of data through time. Moreover, an extract of all existing information provides the first insight into available water resources and it shows gaps of information necessary to quantify various levels of WRA. Using the review (inventory) results, preliminary assessments can be made of the priority factors for WRA in the study area, and appropriate plans for additional investigations can be made to secure collection of new or missing data and reprocessing of old data using modern methods that can yield new information.

There is always some existing information relevant to an assessment of water resources. Previous studies, varying from countrywide assessments to detailed studies on a local scale, can contain valuable information. Additionally, but often overlooked, the use of analogies from other regions with similar hydrogeological settings can provide significant additional insight.

Concept of information

During the process of water resources assessment, data, information and knowledge are required. Demarcation of the terms is important for setting conditions in the process of acquisition, management and sharing.

The terms can be described as follows:

– ***Data***: refers to measured values (for example, discharge volumes, depths to groundwater and concentrations of chemical compounds in groundwater);

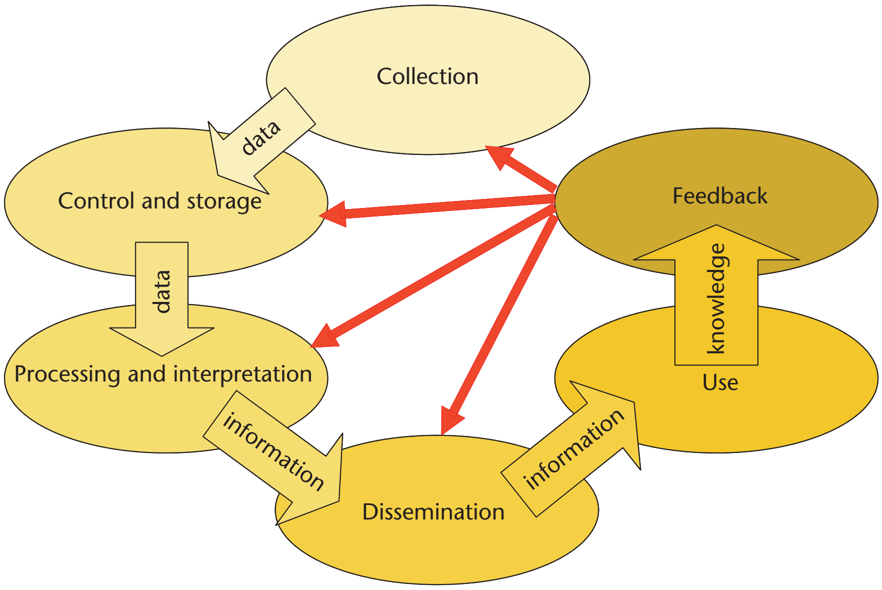
– ***Information***: is obtained by interpretation of data and answering “who”, “what” and “when” questions;

– ***Knowledge***: we can speak about knowledge if we apply information to answer the “how” questions (Ackoff, 1989).

Fieldwork to collect or support the collection of data is demanding in time and resources, and large database systems, which can be expensive to develop and difficult to maintain, are often required. The sharing of existing data is often subject to restricted confidentiality agreements or high prices. Information is obtained from data by using interpretation skills, techniques and familiarity with the area concerned. Geographical information systems are now widely used to manage data and information in a spatial sense. In general, information is more easily exchangeable than data.

Knowledge is based on understanding of information and often uses analogies between comparable situations. Knowledge is disseminated through publications, papers, workshops and so forth. There are usually few obstacles for exchange, as the benefits from sharing knowledge are widely acknowledged.

The relation between data, information and knowledge is schematized in Figure 3.1.



Source: Vasak and Van der Gun, 2007

Figure 3.1. Relation between data, information and knowledge

Who needs what type of data and information?

Water specialists, decision-makers and the general public require different types of information on water. Water specialists prefer access to raw but quality controlled data in their own discipline but may profit from processed data, provided that the processing methodology is transparent and well-documented. They are also interested in information sources and techniques used for the interpretation of data. Water specialists look for quantitative information and they make their own statistics.

Decision-makers need information that combines various aspects of water in order to support, for example, regulatory and policy decisions. They prefer graphs, maps and simple aggregated statistics showing dependencies in space and/or time and other relationships.

The general public is interested in easily understandable information without technical details, and usually looks for information giving an overall picture and explaining the main issues.

Primary sources

The first step in a review of existing data, information and knowledge is to know where these are available or who can provide personal help in this quest. The main sources that should be investigated at the start of any WRA are the following:

(a) Any reports, books and manuals reporting on the investigated area;

(b) Any maps and cross-sections, representing parts of the investigated area;

(c) Any digital geographical data that could be used in GIS-based software;

(d) Any raw data collected or relevant to the investigated area. It is important to consider the methods or techniques used to acquire these data, as these provide information on the quality of the data;

(e) Any interpreted data presented in graphs, etc.;

(f) Any persons having any data, information or knowledge needed for the assessment;

(g) Any programmes, conferences and meetings where the investigated area is the subject of discussion;

(h) Relevant newsletters, now often disseminated through the Internet, which might contain relevant information on the investigated area. These newsletters can provide additional up-to-date information on the investigated area and awareness of future plans or projects that could be carried out there.

3.2 TOOLS FOR REVIEWING EXISTING INFORMATION

The relevant data, information or knowledge can be quite extensive and scattered over different organizations. It is thus important to use efficient tools for assessing existing information. Some of these tools are summarized below.

(a) Metadatabases/station histories/drilling reports:
Paper-based reports on stations, some of which will have been digitized or imaged as part of data rescue/conservation projects, provide a wealth of information on the past history of data collection sites and their operation.

(b) Meta information systems:
A meta information system stores information about data sources. For example, if looking for reports on groundwater resources in a certain area, the system will return all titles of existing reports focusing on that subject. It does not store any "scientific" data (measurements, analyses, etc.). It can considerably improve access to a very large amount of information that is otherwise difficult to trace. Though it is a very valuable tool, few meta information systems yet exist.[1] It is a good example of appropriate application of information technology in the context of "information rescue" and "institutional sustainability" for water information.

(c) Project archives and databases:
It is important to consult relevant archives, databases and yearbooks that may contain data or meta information.

(d) Personal communication/network:
To know if or where existing data or information can be found, it is important to consult experts that have carried out projects in the studied area. These experts might also have a lot of valuable knowledge that might not be written down anywhere.

(e) Internet:
The Internet is a powerful tool to quickly investigate any data or information on the studied area that has been published or referenced on the World Wide Web. Some important databases currently available from the Internet that are relevant for a WRA (see section 4.6.1) are listed in Appendix I.

* * *

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[1] The Meta Information Module (MiM) of the International Groundwater Resources Assessment Centre (http://www.igrac.nl) is an example of a meta information system.

CHAPTER 4. DATA COLLECTION, PROCESSING AND QUALITY CONTROL

Each of the key types of data list in section 2.5 is considered in the following sections of the present chapter with consideration of the nature of the data, why the data are required for water quantity and water quality assessment, their availability and how they are analysed and presented.

4.1 DATA COLLECTION

Water resources assessment is fundamentally a data/information collection exercise followed by the presentation of these data/information to provide value added products on the spatial and temporal characteristics of the available water supplies and their usage. Therefore, data collection across the four areas identified in section 2.5 forms the fundamental basis of a water resources assessment. In the end, the assessment will only be as good as the data collected allow. The extent and frequency of the data collection should reflect the variability of the processes in space and time. This material does not address the numerous issues associated with data collection programmes and the user is directed to, for example, the following publications which provide more detailed information on data collection programmes:

– *Guide to Hydrological Practice*s (WMO-No. 168; WMO, 2008*a*)

– *Handbook of Hydrology (*Maidment, 1993)

– *Environmental Hydrology (*A.D. Ward and S.W. Trimble, 1995)

– *Water Resources Assessment – Handbook for Review of National Capabilities* (WMO/UNESCO, June 1997)

4.2 BIOPHYSICAL DATA

4.2.1 Topographic data

Topographic data refer to detailed information about the shape of the Earth surface including ground elevations, rivers, lakes and the location of roads and other infrastructure, administrative boundaries, and surface objects both natural and human-induced. Topographic data comprise information on the following:

– Elevations, often available as a Digital Elevation Model (DEM)
– Relief, often represented on maps by contour lines
– Drainage patterns of surface water bodies (rivers, lakes, streams)
– Infrastructure including highways, roads, railways, power plants, etc.
– Land use (agricultural zones, forests, cities, industrial zones)
– Geographical position (using a projection to a 2-D surface)

Requirement for topographic data in a water resources assessment

Topographic data are valuable information as they provide a first overview of the shape, relief and infrastructure of the studied area. When preparing for fieldwork in the studied area, questions related to the location and accessibility of the investigated area can be answered by accurately observing the topographic data. Topographic data also allow the surface drainage area of catchments or regions of interest to be identified and measured, which is generally an important first step in water resources assessment. Topographic data are also essential in understanding the direction of flow and movement of water through the catchment and/or aquifer.

Water quantity issues

When no up-to-date digital maps of river networks are available, a DEM of the investigated area can be used to define river networks and surface flow catchment boundaries. Variables such as recharge, runoff and abstraction related to relevant areas, for example, catchments or administrative boundaries, can be calculated using the boundaries provided by the topographic information. Additionally, topographic data are essential information when building numerical models (groundwater or surface water models), as differences in elevation are the main force driving surface water flows and often the main force driving groundwater flows.

Water quality issues

Potential sources for water pollution can be identified by using topographic data representing locations of human-made sites such as industrial zones, waste deposit sites, built-up areas (settlements) or areas of intensive agricultural production. It is important to identify whether the area is close to the sea or tidal waters, as interaction with saline water will considerably influence water quality.

Availability of topographic data

Depending on the country or region where the study is carried out, topographic data can be available in different formats:

(a) Topographic maps, which are often available at different scales.

(b) Digital maps or files such as DEM grids to be used in GIS-based software.

On a global scale, DEM grids are available at different resolutions. Before downloading data, it is important to consider the scale at which the WRA is going to be carried out. It is not advisable to download high-resolution data when the investigated region is very large. Data with very high resolution need significant computer memory and skilful processing. Subsequent conversion to lower resolution can involve considerable effort.

As an example, there is an overview of the current products from the United States Geological Survey (USGS).[2] In this case, the Global 30 Arc Second Elevation Dataset (GTOPO30) is a DEM [3] available free of charge with a horizontal grid spacing of 30 arc seconds, approximately 0.9 km. The Shuttle Radar Topography Mission (SRTM) presents data with a grid spacing of 3 arc sec (approximately 90 m). ETOPO5 and ETOPO2 are global elevation databases gridded at 5 and 2 minutes (approximately 9 and 4 km), respectively, and are available free of charge from the National Aeronautics and Space Administration (NASA) National Geophysical Data Center (NGDC).[4] They include both land elevation and ocean bathymetry.

(c) Satellite images or aerial photographs.

Satellite images and aerial photographs are a very useful source of up-to-date data on many aspects of land use. They often have to be paid for, although government agencies frequently hold collections that can be freely available to those employed by, or working for, national governments. Different companies sell these maps and photographs. The aerial coverage and resolution of these products are regularly increasing (see section 4.6.2).

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[2] http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/Elevation_Products

[3] http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info

[4] http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html

As digital data have experienced a developing boom in the past decade, it is wise to browse the Internet for the most up-to-date topographic data available and relevant to the study.

Processing and interpretation of topographic data

When downloading digital topographic data, it is important to consider their scale/resolution, the geographical projection, and the techniques at hand to process and analyse the data (for example, GIS-based software). When working with digital data, downloaded data with different projections can cause problems when superposing and integrating different topographical maps. It is important to transform all data into a chosen common projection.

If the purpose of using topographic data is to define catchment boundaries, several GIS-based techniques can be used, often available in a GIS-based software package. HYDRO1k, available free of charge from the Internet, is a product derived from the GTOPO30. It is a suite of geo-referenced datasets including streams, drainage basins, both raster and vector, which will be of value for all users who need to organize, evaluate or process hydrologic information on a continental scale (http://eros.usgs.gov/).

Presentation of topographic data

Topographic data are almost always presented as maps. It is now even possible to visualize and present the data in three dimensions by using one of the many existing software packages, provided that appropriate digital data are available. When presenting the data, a suitable projection and coordinate system should be used and a scale and orientation should always be included.

4.2.2 **Soils**

The term soil usually refers to unconsolidated mineral or organic matter on the surface that may contain liquid and gases. For purposes of classification, the lower boundary of soil is arbitrarily set at 200 cm (Joint Research Centre of the European Commission, 2012).

The classification of the Food and Agriculture Organization of the United Nations (FAO) and UNESCO (ISRIC, 1994) distinguishes 28 major soil groupings and a total of 153 soil units. To characterize soil for water resources assessment purposes the following data are required:

- *Soil texture* represents the relative composition of sand, silt, clay and organic matter in soils. The texture groups include sands, sandy loams, loams, clay loams, light clays, medium-heavy clays and peat soils;
- *Soil structure* refers to how soil particles are grouped or arranged;
- *Soil depth* is determined by the total thickness of layers affected by soil forming processes. The soil layers are generally underlain by undisturbed “parent material”. Deep soils usually refer to soils deeper than 1 m;
- *Slope class* indicates the slope that dominates the area of a soil association. Three classes are distinguished: level to gently undulating (0–8 per cent), rolling to hilly (8–30 per cent) and steeply dissected to mountainous (over 30 per cent). The effect of slope on runoff and erosion differs with the soil group and with climate (ISRIC, 1994);
- *Soil moisture* content refers to the water content of a defined soil sample;
- *Chemical analysis* includes both solid phase and fluids. Standard soil analyses should include pH, electrical conductivity, iron pyrite content, nutrients, organic matter content and cation exchange capacity (CEC). In special cases, chemical analyses should also allow quantification of hazards such as heavy metals and dense non-aqueous phase liquids (DNAPL).

Requirement for soil data in water resources assessment

Water quantity issues

Soil data can help to parameterize various models:

- Soil moisture models
- Precipitation runoff models
- Groundwater recharge models, etc.

For example, soil moisture data are used to determine water fluxes and evaporation rates. The slope class may be used to estimate the runoff and erosion within various soil types and climate zones. Soil data may also be used in estimates of groundwater recharge (section 8.5).

Water quality issues

Soil particle size influences transport of pollutants into groundwater. Soil type can also affect surface water contamination. The mineral composition of soil, organic matter contents and available gases have a huge effect on the composition of groundwater through various geochemical and biochemical reactions (see section 8.6).

Availability of soil data

Many countries have a national soil survey that furnishes soil maps and reports. A compendium of online soil survey information (soil geographical database) is available at the Faculty of Geo-Information Science and Earth Observation (ITC)[5] and in Rossiter (2005).

Datasets on various scales can also be obtained from ISRIC World Soil Information.[6] Many agricultural reports contain soil data.

On the global scale the best source of this information is the Soil Map of the World, which was produced by FAO and UNESCO in 10 volumes between 1970 and 1978. It provides the most detailed, globally consistent, soil data. The Digital Soil Map of the World (DSMW) CD-ROM is based on the FAO/UNESCO Soil Map of the World (original scale 1:5 000 000). The CD-ROM contains two types of files, DSMW map sheets and derived soil property files with images derived from the Soil Map of the World.[7]

Processing and interpretation of soil data

The processing of soil data includes the estimation of grain-size distribution, volume-mass properties and soil-water curves taking into account mineralogy, permeability, compression, compaction, shear strength, and so forth.

A comprehensive overview on processing sequence and algorithms of soil data from the FAO soil maps is given by NASA (2006).[8]

Presentation of soil data

Spatial soil data are presented on soil maps. If digital soil data are available in required form, geographical information systems may be used to produce thematic maps showing different parameters.

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[5] http://www.itc.nl/~rossiter/research/rsrch_ss.html

[6] http://www.isric.org/

[7] http://www.fao.org/ag/agL/agll/dsmw.htm

[8] http://gcmd.gsfc.nasa.gov/records/GCMD_GNVd0035_104.html

Representative soil profiles provide information on vertical variations in soil horizons. Point soil data, such as results of laboratory analyses, are presented in tables and diagrams.

4.2.3 Geological data

Geological data refer to all data that can give information on the history, composition, structure, physical properties and processes of the Earth. They include, among others, the following:

- Lithological data describing the type and mineralogy of rocks (consolidated or unconsolidated) and their parameters such as grain size and porosit;
- Structural data including faults and folds present in rocks or unconsolidated sediments;
- Stratigraphic data related to the distribution, deposition and age of sedimentary rocks;
- Geochemical data quantifying the chemical composition of rocks and describing the results of various processes, for example, the presence of chemical erosion resulting in the development of karst zones.

Requirement for geological data in a water resources assessment

Water quantity issues

Geological data give basic information on the hydrogeological setting of a region. In the area of interest, aquifers, aquitards, aquicludes (see definitions in section 8.1), recharge zones and discharge zones (seepage and springs) of groundwater are defined by investigating the geology. Permeability can be deduced from the lithology and structures of rocks and unconsolidated deposits. The grain size of a rock defines the primary permeability. The structures and erosional features such as karsts define the secondary permeability. When no soils are present on top of geological formations, runoff can also be estimated by observing, among others, the permeability of the outcropping rocks or sediments.

Water quality issues

When studying the groundwater chemistry in an area, it is essential to assess the natural background concentrations of the major, minor and trace components. These natural background concentrations can be determined using data on the chemical composition of the aquifer rock and groundwater, the physical properties (permeability) and the hydrodynamics (recharge, discharge, flow paths).

Availability of geological data

Many countries have a national geological survey where geological data, information or knowledge is available. The extraction industries (oil, gas, mines), if present in the area of interest, often own a lot of sound geological data, but such data are difficult to obtain, as these are often confidential. Depending on the law in the country and the policy of the company, these data may or may not be available. Also, many countries have well drilling companies or units that hold geological data and information.

Useful sources include geological reports, geological maps, geological cross-sections, borehole completion forms and results of geophysical investigations (seismic profiles, electromagnetic studies, resistivity surveys, and so forth).

On a global scale, a source to consider is the Commission for the Geological Map of the World (CGMW).[9]

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[9] http://ccgm.free.fr/cartes_monde_gb.html

Processing and interpretation of geological data

Geological data should be translated to hydrogeological data by observing the different lithologies and structures present in the rocks and unconsolidated deposits and estimating the corresponding hydraulic parameters (permeability, porosity). The distribution of the different hydrogeological layers can then provide insight into the potential recharge, recharge zones, discharge zones/springs, runoff and the relation between surface water and groundwater in the investigated area.

Specific computer software can be used for production of digital geological models providing digital geological data are available (for example, top and bottom of geological layers). These geological models can then be converted to hydrogeological models. Different types of software exist, but all require specialist training before they are used professionally. Digital mapping technology can be applied to traditional geologic mapping, reconnaissance mapping and surveying of geologic features. At international digital field data capture (DFDC) meetings, major geological surveys (for example, the British Geological Survey and the Geological Survey of Canada) discuss how to harness and develop the technology. Many other geological surveys and private companies are also designing systems to conduct scientific and applied geological mapping of, for example, geothermal springs and mine sites.

Presentation of geological data

Maps, cross-sections and stratigraphical columns are usually used to present the geology in an area. Presentation of the geology in 3-D is also now possible and very illustrative owing to the continuing development of new software.

4.2.4 **Natural vegetation data**

Data on natural vegetation include the following:

- Categories of plants, for example, grasses, shrubs and trees
- Species in each of the plant categories (although this is normally only of secondary importance)
- Temporal and spatial variations in vegetation patterns

Requirements for natural vegetation data in water resources assessment

Water quantity issues

The distribution of precipitation falling on the ground surface is modified by the presence of vegetation. This process, called interception, is a function of the branching structure and leaf density. Vegetation cover also influences evapotranspiration and infiltration. These processes are important in assessment of runoff and groundwater recharge. Revegetation of recharge areas can slow or reverse rising groundwater tables and ameliorate dry land salinity. Identification of natural vegetation species in semi-arid and arid areas helps in assessing shallow groundwater.

Water quality issues

Natural vegetation is an important ecological indicator of water quality. Interaction of natural vegetation with soil initiates various chemical and biological reactions that have a pronounced influence on groundwater quality. Removal of natural vegetation (for example, deforestation) can cause erosion in the catchment area. Erosion creates an overload of suspended material in rivers and surface water reservoirs.

Availability of natural vegetation data

Vegetation maps, satellite images and aerial photographs are main sources of spatial distribution of vegetation. Worldwide vegetation mapping at regular intervals and dissemination of data are done by several agencies at different scales. To avoid images with clouds, a decadal (10-day) Earth Observation Satellite Normalized Difference Vegetation Index (SPOT-NDVI) series with 1-km resolution can be downloaded for free at http://free.vgt.vito.be/. The data are radiometrically corrected and pixel values are in radiance values on top of atmosphere (W m^{-2} sr^{-1} mm^{-1}) in order to enable mutual comparison. The monitoring of the vegetation index through time can replace the static "land cover" input in hydrologic models. If higher resolution is required, MODIS images at 250-m grid spacing are available, free of charge, for every point in the world every 1–2 days in 36 discrete bands.[10]

Reports on the state of the environment, available for most countries, contain information about (natural) vegetation species and the ecosystems of which they are a part.

Processing and interpretation of vegetation data

Remote-sensing data provide valuable information for mapping vegetation and monitoring vegetation change (seasonal and long term).

Vegetation monitoring has been one of the main focal points of remote-sensing study since this area of research began. Many vegetation indices, using red and infrared reflectance, have been devised. Vegetation index definitions and formulae used in the processing of remote-sensing data are given by Fleming (2000).

Presentation of vegetation data

Distribution of vegetation is presented on vegetation maps. To evaluate vegetation changes in time, satellite images and aerial photographs for selected periods should be displayed. Data on major vegetation species are usually stored in a (digital) catalogue.

4.3 HYDROMETEOROLOGICAL DATA

Hydrometeorological data cover all the various components of the hydrological cycle – climate parameters, such as precipitation and evaporation, surface water and groundwater. Measurements of these hydrological cycle components are the vital building blocks that contribute to water resources assessment.

4.3.1 Climate data

Climate data include precipitation, temperature, humidity, solar radiation and wind speed, of which the latter four enable estimation of evaporation.

Requirement for climate data in water resources assessment

Water quantity issues

The types of climate data required are those of the input to the catchment, namely precipitation in the form of rainfall or snow, and those concerned with estimation of snowmelt and evaporation losses, namely temperature, humidity, solar radiation and wind speed. Precipitation is measured primarily through networks of raingauges, although increasingly other sources of data, such as weather radar or remotely sensed data, are now becoming available. Raingauge networks are generally fairly good in most countries, although coverage is often poor in remote and mountainous areas. This is unfortunate, as precipitation is generally higher over upland areas than at lower elevations owing to orographic effects, and allowance for these altitude effects should be built into assessment of areal precipitation (see section 5.5).

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[10] NASA MODIS: http://landweb.nascom.nasa.gov/ and http://rapidfire.sci.gsfc.nasa.gov/subsets/

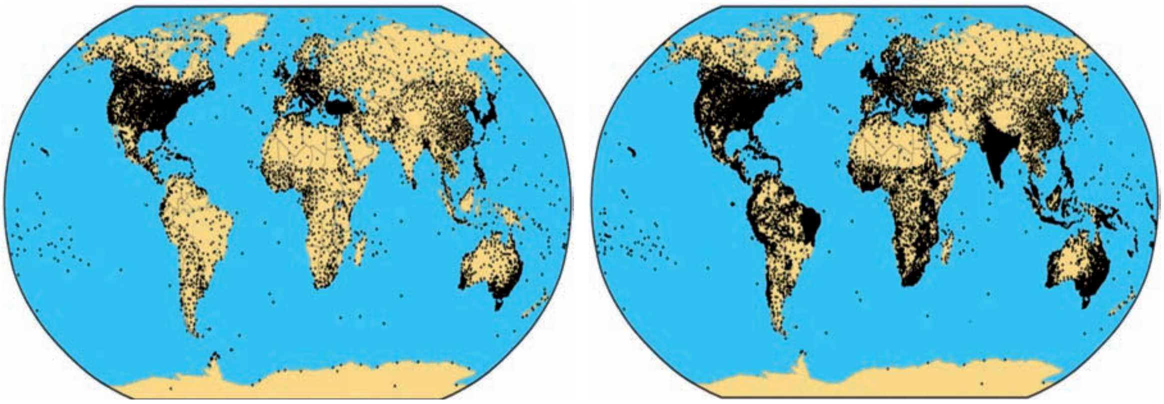

Figure 4.1. GHCN air temperature network (left) and GHCN precipitation network (right); available online at http://www.ncdc.noaa.gov/ghcnm/

Water quality issues

Climate data are not of primary importance when considering water quality, at least not when considering water resources assessment. The issue of acid rain is one that may be of concern for some groups, but is not one that should concern those involved in basic assessment of the quantities and basic quality of water resources; in general, precipitation quality is not a major concern to those involved in WRA. Stable isotope signature of precipitation (ratios of the isotopes of oxygen and hydrogen) can improve the understanding of the hydrological processes in the region.

Availability of climate data

Precipitation and temperature

Several worldwide archives of monthly temperature and precipitation have been constructed using raw data from meteorological stations. Archives differ in spatial coverage, length of the data records and number of stations. The comprehensive overview of the available archives and downloadable data may be found at the dedicated website of the World Data Center for Meteorology (WDC, http://www.ncdc.noaa.gov/oa/wdc/index.php).

One of the archives accessible through the WDC that meets the criteria for hydrological calculations is the Global Historical Climatology Network (GHCN) dataset (Smith and Reynolds, 2005; Smith et al., 2005). GHCN-Monthly contains records of mean temperature data for 7 280 stations (Figure 4.1, right). Most of the records are for a century-scale period of observations; however, the minimum requirement is 10 years of data. Precipitation data are available for 20 590 stations (Figure 4.1, left). It is apparent from Figure 4.1 that the density of observational network varies by region. In general, the best spatial coverage is evident in North America, Europe, Australia and parts of Asia, and coverage in the northern hemisphere is better than in the southern hemisphere.

Archives based on the raw observations provide high-quality climatic information in regions with dense observational networks but often do not meet such high standard criteria where observations are sparse. Efforts have been made to develop high-resolution gridded datasets using different interpolation routines and reanalysis of data from a large number of weather stations. The most commonly used gridded products available online are described below.

The Climatic Research Unit (CRU) in the United Kingdom of Great Britain and Northern Ireland has developed several datasets comprised of monthly grids of observed climatic characteristics covering the global land surface at varying resolutions from 0.5° to 5.0° lat/long (Mitchell and Jones, 2005). One of the high-resolution (0.5° lat/long) datasets, CRU TS 2.1, has been specifically reformatted to be used in hydrological calculations by the International Water Management Institute (IWMI). Data and supporting documentation are available at http://www.cgiar-csi.org/.

Anomaly grids were combined with the gridded 1961–1990 normals (CRU CL 1.0; New et al., 1999) to obtain absolute values for the period 1901–2002. The 0.5° gridded data for 1901–2000 are available from the United Kingdom Tyndall Centre website[11] (Mitchell et al., 2003). Similar datasets are available from NASA.[12] However, such datasets are aimed primarily at researchers and there may be restrictions on their use. The Tyndall Centre stipulates that the data may only be used for "non-commercial scientific and educational purposes", provided that they are properly described and attributed. Thus such data may not always be accessible to those undertaking WRA as paid consultants, although data will often be made available if the data request comes from a national or regional government agency.

The Willmott and Matsuura Arctic climate dataset (W&M) was developed in the Department of Geography at the University of Delaware in the United States. This archive is fully documented and data are available for download at http://climate.geog.udel.edu/~climate. Monthly-mean air temperatures and precipitation calculated for a varying number of land-surface weather stations (between 2 000 and 12 000 in different time periods) were used to produce a global gridded archive with 0.5° latitude and longitude resolution (Willmott and Rawlins, 1999). The accuracy of the interpolation was assessed by station-by-station cross-validation. Currently the resulting dataset provides monthly means of air temperature and precipitation for the 1900–2010 period.

A 40-year reanalysis (ERA-40) of monthly air temperature and precipitation output from atmospheric reanalyses is available from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR). The atmospheric reanalysis projects provide long-term time series of analysed atmospheric fields and modelled surface fields based on frozen forecast and data assimilation systems (Serreze et al., 2005).

The original ERA-40 2-m air temperature output contains temperature at six-hour intervals in a reduced Gaussian grid (N80) with approximate resolution of 125 km, and covers the period September 1957 to August 2002 (Kallberg et al., 2004). The six-hour air temperatures are averaged arithmetically into daily and monthly values. ERA-40 air temperature from forecasts for the 2-m level are post-processed, interpolated between the lowest model level and the surface, and assimilated with ground-based measurements (Betts et al., 2003). ERA-40 precipitation is a modelled (or forecast) field not influenced by ground-based measurements. The ERA-40 reanalysis data are available from the ECMWF website.[13]

The NCEP-NCAR reanalysis starts in 1948 and is updated continuously.[14] The NCEP-NCAR 2-m air temperature is a standard modelled field, produced by linear interpolation between the surface skin temperature and the temperature at the lowest model sigma level (0.995). It is, therefore, influenced strongly by the modelled surface energy budget. Air temperature at the lowest sigma (0.995) level is not influenced as strongly by the modelled surface energy balance, and should provide for relatively realistic temperature variability (Oelke et al., 2004). Unlike the ERA-40 2-m air temperature, the NCEP-NCAR 2-m air temperature is not assimilated with ground-based measurements. NCEP-NCAR precipitation is also a standard modelled field of the NCEP-NCAR reanalysis. More details on NCEP-NCAR reanalysis may be found at http://dss.ucar.edu/pub/reanalysis/.

Uncertainties in precipitation and temperature data

Several studies have tested the accuracy of gridded datasets. Fekete et al. (2004) analysed the uncertainties in precipitation and the effect they have on the hydrological modelling through

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[11] http://www.cru.uea.ac.uk/~timm/grid/CRU_TS_2_0.html

[12] http://data.giss.nasa.gov/precip_dai/

[13] http://www.ecmwf.int/

[14] The NCEP system was described by Kalnay et al. (1996), Kistler et al. (2001), and in references cited by them. Serreze and Hurst (2000) also provided a brief overview of the NCEP system.

intercomparison of different global archives. The datasets were climatologically averaged and compared by calculating various statistics of the differences. The climatologically averaged monthly precipitation estimates were applied as inputs to a water balance model to estimate runoff and the uncertainties in runoff arising directly from the precipitation estimates. The results indicated the need for accurate precipitation inputs for water balance calculations. These results also demonstrate the need to improve precipitation estimates in arid and semi-arid regions, where slight changes in precipitation can result in dramatic changes in the runoff response due to the non-linearity of the runoff generation processes. Details of such a comparison may be found in Fekete et al. (2004).

Anisimov et al. (2007) compared temperature characteristics derived from four gridded datasets with observations at 455 weather stations in the Russian Federation. As was the case with precipitation, the results of this study indicate large region-specific uncertainties in the temperature.

Other data sources

Information on snow is more difficult to obtain, as although the extent of snow cover may be obtained from aerial photography or satellite imagery, associated information on depths, density or water equivalent is often very difficult to obtain; such data are rarely adequately measured in a routine manner. In a number of countries using satellite data for monitoring of snow cover, algorithms have been developed to estimate snow depth or snow water equivalent. As these relationships are sensitive to local characteristics, caution is required when applying them in other areas.

The other climate parameters required to estimate evaporation or to allow calculation of snowmelt are generally available only from relatively sparse networks of climate stations, either operated by national meteorological agencies, by irrigation schemes or by research stations. Fortunately, evaporation is a relatively conservative variable that is fairly constant over large areas, and hence the limited spatial coverage of such stations may not always be a major problem. However, the problems of estimation of reduced evaporation over upland areas is similar to the orographic enhancement of precipitation, and some adjustment of low elevation evaporation estimates may be necessary (see Chapter 6). Furthermore, it should be noted that evapotranspiration can be a significant component of groundwater balance particularly in arid and semi-arid countries (Meijerink et al., 2007).

4.3.2 **Surface water data**

Surface water data of relevance to WRA primarily refers to river discharge (or flow), although the quality of such waters is also important. It also includes quantities of water held in natural lakes, wetlands, soils and human-made reservoirs. Soil moisture is dealt with elsewhere in the present publication and is not generally routinely measured in most countries, although it may sometimes be estimated through areal water balance modelling as the difference between precipitation inputs and river flow, groundwater recharge and evaporation outputs.

Requirement for surface water data in water resources assessment

Water quantity issues

River flow data are one of the most important sources of information in WRA, as river flow represents one of the main sources of water for human and animal consumption, irrigation and navigation, as well as a source of hydroelectric power. Guidance for undertaking river flow computations can be found in the *Manual on Stream Gauging* (WMO, 2010) and in the WMO *Technical Regulations* (WMO, 2006). However, river flow is just one element of surface water data. Information on lake, dam and reservoir levels and volume, dam and reservoir releases and transmission losses is also important in assessing the availability of water.

Water quality issues

The quality of surface water is a key determinant in availability of water for the above range of uses and assessment of environmental quality. Water quality is one of the key factors in determining the "fit-for-purpose" nature of a water supply. For example, water of a given quality can be used for domestic stock watering, but may not be suitable for irrigation and/or public water consumption. Data collected from ambient water quality monitoring programmes are used for a variety of purposes, including the following:

- Quantity and quality condition and trend monitoring and reporting;
- Supporting other department aquatic ecosystem health monitoring and assessment programmes;
- Detection of anthropogenic pollution, for addressing which measures should be taken;
- Assessment of suitability of water for use and the treatment needed.

Availability of surface water data

Surface water records of river flow, lake and reservoir levels will ideally be collected and stored by national and regional hydrometric agencies. Others such as water supply or hydropower companies as well as large irrigation operators may well have long-term records. Ideally, river flow records should span at least 30 years or more in order to characterize reliably the long-term mean flow and seasonal and interannual variability.

A further valuable source of river flow data is the Global Runoff Data Centre (GRDC)[15] that holds a large number of river flow records from generally the larger, more important rivers in many countries. However, such data have generally originated from the national hydrological agencies in each country, and hence the data should already be available to those involved in national or regional water resources assessments. Similar restrictions apply to the GRDC data as for the Tyndall Centre precipitation data described in section 4.3.1 above, and use by commercial consultants may be a problem.

Water quality is often monitored on a routine basis by regulatory authorities and it is important that records cover a broad range of flow conditions and seasonal variations.

Processing and interpretation of surface water data

River flow cannot easily be measured directly, but is generally computed from records of river water level converted to flow, or discharge, using a rating curve or table. A rating curve is a relationship between river level, or stage, and river flow or discharge and, except where sited at specifically designed hydraulic measuring structures, must generally be derived for each gauging station over a number of years by measuring discharge over a wide range of stage (river level). Obtaining adequate low and medium flow gauging is relatively easy, but being able to gauge sufficient high flows is often difficult. Unless local information on river levels is transmitted back to central offices in real time, specialist staff may not be able to get to gauging station sites before the flood peak has passed. Details on derivation of rating curves may be found in Herschy (2009) or WMO (2010).

Water levels for lakes and reservoirs will normally be converted into storage volumes using appropriate area measurements.

For further discussion of surface water flow analyses, see Chapter 7.

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[15] http://www.bafg.de/GRDC/EN/Home/homepage__node.html

Presentation of surface water data

Surface water data will usually be stored as databases of level, flow or water quality related to the time of measurement so that time series can be plotted.

4.3.3 Groundwater data

Groundwater data in general refer to all data that are necessary to assess aquifers, groundwater quantity and groundwater quality. They include a large number of parameters related to geological, hydrogeological and climatological conditions as described in Chapter 8.

In hydrogeological studies, groundwater data can be classified into four levels on the basis of the degree of interpretation as set out in Table 4.1 (Struckmeier and Margat, 1995).

Requirement for groundwater data in water resources assessment

Water quantity issues

Groundwater data are required to specify the location and geometry of groundwater reservoirs, to quantify the volume stored in these reservoirs and to understand the dynamics of groundwater systems. Groundwater data are also required for evaluation of the interaction between groundwater and surface water resources.

Water quality issues

The quality of groundwater directly influences its use for drinking (domestic), agricultural and industrial purposes. Groundwater composition can also be used to define the origin of water and to follow its movement from recharge to discharge areas (tracers).

Table 4.1. Classification of groundwater data

	Hydrogeological features	*Groundwater features*	*Anthropogenic features*
Basic data (Direct observations or measurements)	Location of observation point (x,y,z); characteristics of outcropping strata; depth of top or base of aquifer; aquifer thickness; aquifer characteristics	Location of observation point (x,y,z); depth to groundwater; spring discharge; pH; conductivity; temperature; chemical analyses	Location of well, bore, shaft (x,y,z); depth of well; well discharge; drawdown
Primary data (Simple interpretation of basic data)	Hydrogeological boundary; elevation of top or base of aquifer; isopachs or structural contours of aquifer	Potentiometric contours; hydrographs; mean spring discharge; salinity contours; isotope analysis	Position of screen relative to mean sea level; mean well yield; mean abstraction or injection; maximum drawdown
Secondary data (for example, derived from more complex spatial, statistical or numerical analysis)	Aquifer parameters, for example, porosity, permeability, transmissivity; grain size analysis	Boundaries of phreatic, confined, artesian groundwater; flow directions and velocities; groundwater divides; interactions between groundwater system and river; recharge and discharge fluxes	Specific yield; artificial recharge
Tertiary data (Information – interpretations used for decision-making)	Accessibility; risk of drilling failure; possibilities of leakage; level of aquifer protection	Groundwater quality; suitability; vulnerability; protection areas	Sustainable productivity; mean abstraction per unit area; injection potential; pollution

Source: after Struckmeier and Margat, 1995

Availability of groundwater data

Data about groundwater is collected and compiled by private consultants and many local, regional, national and international organizations. Field surveys including hydrogeological reconnaissance, exploratory drilling, well inventories and monitoring programmes (water levels and water quality) are the main sources of (unprocessed) groundwater data. Data from these activities should be stored in databases and made available to various users.

Hydrogeological maps, technical reports and publications are main sources of processed and interpreted groundwater information. Collection of data required to quantify specific groundwater parameters is further discussed in Chapter 8.

Processing and interpretation of groundwater data

Processing and interpretation of groundwater data include a large number of mapping techniques, analytical approaches and statistical methods. Theoretical bases of these techniques and methods are described in hydrogeological handbooks (for example, Fetter, 2000). See Chapter 8 for further information on processing and interpretation of groundwater parameters.

Various software packages for processing and interpretation of data on groundwater quantity and quality have been developed. These packages are available as public domain or commercial software. The International Groundwater Resources Assessment Centre (IGRAC) made an inventory of tools for data processing and interpretation. The inventory focuses on the following:

- Low-cost, user friendly software, developed for data storage, screening, validation, verification, analysis and presentation;

- The fields of hydrogeology, borehole and well logging, pumping tests, groundwater levels and discharge, and soil and groundwater quality.

The results of the inventory are described in a report (IGRAC, 2005). This report gives an overview of useful tools identified for groundwater data processing and interpretation, together with information on how they can be obtained and at what cost. Background information on these tools is in the IGRAC online database (http://www.igrac.nl: Meta Information Module).

Presentation of groundwater data

Classical presentation of groundwater data includes hydrogeological maps, cross-sections and a large variety of graphs and figures for water quantity and quality. A recent overview of the presentation of groundwater point and spatial data with examples for both quantitative and qualitative aspects is given by Kovalevsky et al. (2004).

The technology now exists for continuous collection, transmittal and processing of groundwater level data and groundwater quality data to a central location for display of real-time groundwater conditions over the Internet when the data are needed most.

Groundwater information systems allow for viewing of required information according to standard GIS procedures.

4.4 SOCIO-ECONOMIC DATA

Nationally consistent, ongoing sources of socio-economic data capable of supporting water resources management programmes include the following:

- Land use surveys
- Natural resource management surveys
- Agricultural census and surveys
- Farm surveys
- Domestic water supply surveys
- Demographic surveys

While there is a standard classification of industries and a substantial number of attributes of farm families/managers are commonly collected, the information does not necessarily link type of enterprise, land manager or the farm household, and changes in resource condition. The majority of socio-economic information is not point source, but by local area/survey region and thus not always spatially consistent with water resources information. Progress in this area can be achieved through activities such as the following:

(a) Making available confidential unit record files (CURF) from the agricultural census;

(b) Instituting mesh blocks (geographical units for processing census data) as a basic unit of output;

(c) Establishing linkages between the population and housing census and the agricultural census at the mesh block level.

Statistical agencies report on sources, geography and frequency of collections and provide information on nationally available data on human capital, social capital, produced economic capital, participation in water resources management programmes and water users' attitudes and behaviours.

4.4.1 Land use/land cover

Land-use data record the human-related use to which land has been put. Typical categories of land use include agricultural, horticultural and arboricultural uses split between major crop types and distinguishing between irrigated and non-irrigated crops; urban and suburban land; significant industrial and commercial sites; and major mining or other operations.

Requirements for land-use data in water resources assessment

The type of land use affects the processes of soil and groundwater infiltration and also identifies the major areas of water use, whether for irrigation, public supply or industrial processes. Land-use and land management practices can also have a significant impact on runoff.

Availability of land-use data

Much land-use data can be extracted from general mapping, although not all mapping produced for general purposes can be relied upon to use consistent definitions for the boundaries of different areas, and at the more detailed level it may be necessary to use aerial or satellite imagery to distinguish between urban and suburban areas and multispectral imagery to distinguish between different crop types. The Global Land Cover Facility (GLCF) provides Earth science data and products to help everyone to better understand global environmental systems. In particular, the GLCF develops and distributes remotely sensed satellite data and products that explain land cover from the local to global scales.

Primary data and products available at the GLCF are free to all via FTP. Online datasets may be accessed electronically through the Earth Science Data Interface (ESDI).

Processing and interpretation of land-use data

Shape files for each land-use type need to be extracted from mapping or photography and imported to a common mapping system or GIS. Where data such as cropping patterns are inferred from remote sensing it will be desirable to carry out a reasonable level of ground truthing to verify the results.

Presentation of land-use data

Land-use data will normally be presented in mapped form, preferably as layer(s) in a GIS system. Changes over time will normally be presented through map overlays or GIS layers.

4.4.2 Demography

The most significant areas of demographic data for water resources assessments are population density and socio-economic status.

Requirement of demographic data for water resources assessment

Water use for human consumption and direct family subsistence cultivation is highly dependent on the number of people and their socio-economic circumstances. As families become wealthier they will tend to use water of a higher quality for washing, domestic appliances and amenity uses.

Availability of demographic data

Basic demographic data for each administrative area of the country should normally be available from government statistical offices. Projections of population growth, movement and development may also be available. Estimates of population in a selected area can be made with the LandScan model of the Oak Ridge National Laboratory, which uses spatial data and imagery analysis technologies and a multi-variable dasymetric modelling approach to disaggregate census counts.[16]

Processing and interpretation of demographic data

It may be necessary to make assumptions on the divisions of population between different catchments or water-use areas. Past trends and future projections will be useful for the interpretation of water-use data and estimation of future needs. The potential limitations of national census data need to be recognized.

Presentation of demographic data

Data will normally be presented in mapped and tabular form showing the distribution of populations by socio-economic group and illustrating past trends and future projections.

4.5 WATER-USE DATA

Historical water-use data identifies the main demands on the water resources of an area for human, industrial and agricultural use. It will normally be necessary to distinguish between consumptive and non-consumptive use. It is important to also distinguish between the demand or perceived need for water, the actual amount of water withdrawn or extracted and the amount of that water that is actually used for the purpose intended.

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[16] Detailed information is available at http://www.ornl.gov/sci/landscan/. The product is global in coverage.

Although water-use data are not always collected by NHSs, international best practice is pointing to the need for integrated water resources management and development, if sustainability is to be achieved. The African WRA programme (Mott MacDonald International et al., 1992) emphasizes that agencies in charge of water resources information systems should be willing to improve their efficiency, productivity and to take initiatives and participate in the water resources development process. This can be achieved by improving contacts with policymakers and decision-makers to ensure that information requirements are “demand-driven”.

Where water-use data are collected at all, they are usually kept (or lost) by the water user in its raw state and seldom published. Many different organizations may have needs for access to, or responsibility for, water-use data. Where there is no obvious overall responsibility for collection, processing and publication, it may be appropriate for the NHS to take the initiative in clarifying roles and responsibilities in the national, regional or local context.

Requirements for water-use and demand data in water resources assessment

As a river catchment becomes increasingly developed by abstractions from and discharges to rivers and aquifers, so it becomes increasingly important to collect data describing human interference with the natural hydrological cycle. Highly developed rivers need to be “naturalized” before standard hydrological analysis may be carried out. Data are often required on both the quality and quantity of abstractions and discharges. The most significant impact in the Southern African Development Community (SADC) region is likely to result from urbanization and the relentless growth of peri-urban areas.

The pattern of current and projected water use will be a key consideration in determining resource availability for future activities and assessing the reliability of future supplies.

Availability of water-use data

Where possible, actual abstraction figures, over a representative period of time, from major users such as water supply providers, major industrial plants and irrigation operators should be used. Where a water licensing system operates, such records will often be a requirement of the licensing authority. Where actual figures are not available, and to take account of small abstractors, then estimates may well have to be made based on standard data for the relevant populations, industrial processes or cropping systems.

Gravity abstractions and discharges are usually measured by standard hydrological techniques such as weirs, flumes or electronic methods. Flows in pipes can be measured by a variety of devices and pumped flows can be derived from the pump characteristics and hours operated.

Historical data for principal components of water use is essential, particularly if highly developed or artificial streamflows are to be naturalized. Much can be learned from analysing trend changes in water-use patterns.

Increasingly water supply organizations are monitoring consumption around the clock in local water supply districts to monitor distribution leakage. This may also apply in hi-tech irrigation systems.

Aerial surveys and remote sensing are sometimes used to estimate seasonal water use over very large irrigated areas where direct measurement is impracticable. Sample measurements of water use from smaller pumped sources can be made where no permanent method exists by temporarily introducing a measuring tank with v-notch gauge.

Processing and interpretation of water-use data

Just as many NHSs publish hydrological reference data, so organizations responsible for water-use data should publish summaries of abstractions and discharges by river basin and category of use. This information should be compared with water availability, both in an average and a drought year. The United States Geological Survey and the Australian Water Resources Council provide good examples of such publications.

A useful subregional benchmark for the adequacy of water availability and water-use data is provided by South Africa's 1985 "Red Book", which gives a near complete annual water balance, including use, for some 20 regions, and sub-drainage catchments. (Officers from the Department of Water Affairs can advise on the required capability and the staff and skills currently invested in updating this database.) Zimbabwe's "Blue Book" provides another example of water availability and water use and this too is being updated with modern database and GIS systems.

Physiographic data are not often required in connection with water-use data. One particular exception might be the use of topographic data to indicate water pressure in the water supply distribution system as a key factor in mains leakage.

Water-use data requires careful inspection and checking for temporal and spatial consistency, particularly by comparison with similar users. Standard graphical presentations (trends, histograms, pie diagrams and so forth) are useful and readily available with spreadsheet and database packages.

The basic equation used in preparing water management budgets for a basin or sub-basin can also be applied to large-scale water users such as municipal water boards or irrigation districts to determine efficiency in transmission, distribution and local use. Losses can often be 25–50 per cent, or even higher, and these should be reduced before new resource developments are contemplated. In a number of European countries (Czech Republic, Spain and the United Kingdom), they are now down to 20 per cent or below. In a few countries, such as Germany and Denmark, losses are down to 10 per cent or even lower, which is probably close to the limit of what is technically and economically feasible (European Environment Agency, 2010). This is the key to effective water resources management.

Water-use volumes for each category of use should be summed for each sub-catchment as average daily or monthly figures. Where there is significant variability then maximum and minimum demand figures should also be recorded.

Presentation of water-use data

As a minimum, known water-use data will normally be presented in tabular form for each sub-catchment of the study area. Where possible, locations of major use will generally be mapped to show the spatial distribution of such demands.

4.6 SOURCES OF DATA

This section aims to set out some of the generic sources of data, not specifically covered in sections 4.1 to 4.4 above, which are likely to be available. It cannot provide a definitive list for all studies but should provide some starting points.

Meteorological agencies

Meteorological agencies are the primary source of climate data used in a WRA. They provide long-term records of both temperature and precipitation. The spatial resolution of these records can be limited, but temporal variability is well captured. These records can be supplemented with precipitation records from irrigation scheme operators, water supply/sewage operators and industry members, which can aid in building a higher spatial resolution dataset. These records can vary in length but they can make a valuable contribution to datasets using similar gap-filling and record-extension methods to those described in section 7.1.

Hydrological agencies

National hydrological agencies constitute the primary source of hydrological data for a region or river basin. They can exist within a region's or basin's meteorological agencies but specifically collect and process surface water and groundwater information. Other sources of hydrological data include irrigation scheme operators, water supply agencies and hydropower operators.

Geological surveys

National geological agencies are the primary and commonly the only source of geological surveys needed for a WRA. In some cases, they may have responsibilities related to groundwater monitoring. Oil and mineral exploration companies do collect detailed geological data on certain areas, but this information can be difficult to access.

Irrigation departments

Irrigation departments can provide information on water use and quality for the agricultural sector. They commonly collect information on water availability and streamflow but are generally a supplementary rather than primary source.

Statistical agencies

Statistical agencies provide statistics that are used to inform research, discussion and decision-making within governments and the community. This information aids a better understanding of a country – people and society; economy; environment; and statistics by area.

Regional agencies

At the regional level, there are many institutions dealing with water information related to different continents (see Figure 4.2). The water sector coordinating unit of SADC is an example of a regional initiative in Southern Africa for sharing data and information. At a smaller regional scale, data and information may also be collated by a variety of transnational bodies and agencies, including those specifically established for management of major transboundary river basins.

Other agencies

Other agencies that can provide information necessary to complete a WRA include hydropower operators, major agricultural and industrial enterprises, particularly those that are major users of water, and other private organizations. Hydropower operators can commonly provide detailed hydrological information on specific rivers, which can supplement broader information gained from hydrological agencies. Industry members can be a good source of water-use data. It is particularly useful when a representative industry body collects water use and availability data. This will most commonly occur in the agricultural sector. Private organizations and individuals who have a personal or academic interest in weather or climate matters, or other aspects of environmental monitoring, may also hold useful records.

4.6.1 Datasets available from the Internet

Global level

Appendix I lists the main datasets available from the Internet with the name of the providing data centre and the corresponding URL. Note that, depending on the dataset, it may be available free of charge, for an administrative fee, or after having signed a user agreement. Also, some datasets are restricted to non-commercial use.

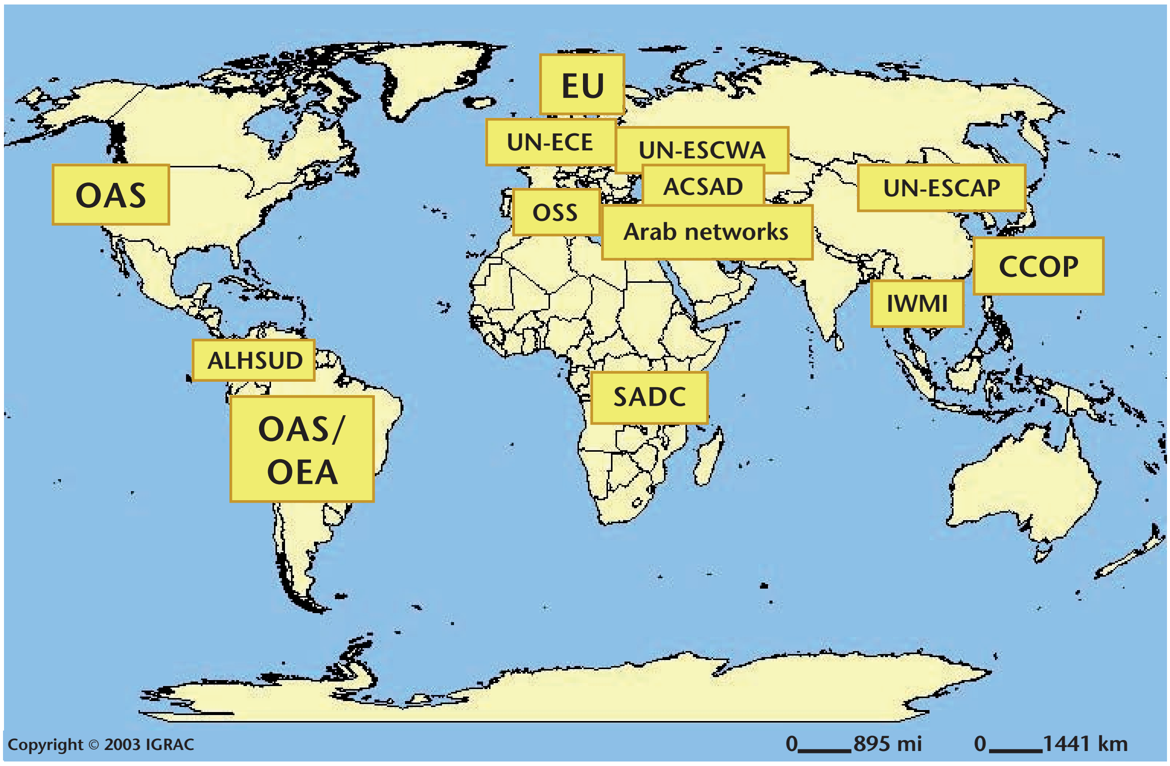
Regional and local levels

The number and range of potential sources is too extensive to list here and, as a starting point it is recommended to browse the Internet to investigate if any datasets are available through the types of institution noted above, as well as the Internet sites of more local organizations.

4.6.2 Remotely sensed data

A variety of imaging sensors onboard satellites and aircraft for Earth observation related to water resources are now widely in use. The most important ones for hydrological applications are the multispectral sensors, which measure the reflectance from the Earth surface in either narrow parts of the spectrum or broader bands and radar sensors, which record either the backscatter of signals emitted from the platform (active radar), or the microwave radiation from the Earth (passive radar). Some key sources are provided in Appendix II. It should be noted that only satellite systems that are still active are listed and low-resolution satellite systems are not included, as they are of limited value for the assessment of water resources.

Apart from such simple measurement as extent of water bodies, remotely sensed data by itself does not give quantities of water. However, it does provide a number of parameters used in physical or physio-empirical methods to estimate areal precipitation and spatial evapotranspiration fluxes, while derivatives of remotely sensed products often provide unique data to be included in models. The main and unique strength of remotely sensed data is the



ACSAD	Arab Centre for the Study of Arid Zones and Dry Lands
ALHSUD	Latin American Association of Groundwater Hydrology for Development
CCOP	Coordinating Committee for Geoscience Programmes in East and Southeast Asia
EU	European Union
IWMI	International Water Management Institute
OAS	Organization of American States
OEA	Organización de los Estados Americanos
OSS	Sahara and Sahel Observatory
SADC	Southern African Development Community
UN-ECE	United Nations Economic Commission for Europe
UN-ESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UN-ESCWA	United Nations Economic and Social Commission for Western Asia

Figure 4.2. Examples of regional agencies that provide water-related data

provision of hydrologically relevant spatial information. Geostationary satellites, such as weather satellites, produce images with short time intervals (for example, the METEOSAT-S-G every 15 minutes) so that dynamic phenomena, such as precipitation and actual evapotranspiration, can be studied. Orbiting Earth-observation satellite systems pass over a given area on Earth with longer time intervals, but processed data, such as a vegetation index, are integrated to build up biweekly time series.

4.7 DATA PROCESSING AND QUALITY CONTROL

Reliable hydrological data and information are key inputs to the sound and wise management of water resources. It is beneficial that hydrological data be of an assured quality that is sufficient for their intended use, such as the operation of water resources systems and overall management of the resource. With a view to achieving their mission and strategic directions, the NHSs have to ensure that their core activities of hydrological data acquisition, services and products are working efficiently and effectively. The implementation of quality management systems will assist NHSs in the provision of good management practices and ultimately will enhance confidence in the quality of the data, products and services.

Particularly under the paradigm of Integrated Water Resources Management, where decisions are increasing being made through a consensual approach including relevant stakeholders, it is imperative that reliable data and information be accessible in a timely manner to facilitate informed decision-making. The value of such data and information increases when they are provided through an organization that values and adheres to quality management.

Depending on a particular country’s circumstances, it is possible that different agencies may be involved in hydrological data collection within a basin. Lack of standard procedures for obtaining measurements, storage of data, data manipulations, and protocols for data and metadata exchange, as well as acceptable analytical methodologies for transferring data into information, may often result in the generation of conflicting information being made available among various sectors, administrative regions and diverse users. Such an occurrence can lead to disagreements, can generate reluctance to cooperate, and can undermine the importance and credibility of the work of the NHS. In transboundary basins, the equation evolves into another level of complexity requiring assurance and reassurance of compatibility and assurances of the quality of data and products at the national and international levels.

Decisions in various sectors of the economy are becoming increasingly dependent on hydrological information generated by NHSs. Given the uncertainties associated with the hydrological processes and the impossibility to eliminate these uncertainties involved in the data and information, it is useful to make the clients aware of these uncertainties. It is also beneficial at the same time to have in place quality management approaches so that assurances can be given that the stated quality of the data is being attained.

Further, research on the global water cycle and impacts of increasing climate variability and potential climate change on the availability of water requires the sharing and use of data from many countries. It is important that in such analyses the data be compatible, comparable and of known assured quality.

It is worth noting that quality management is useful to a NHS even though the Service does not intend to enter into a formal certification process, as the adoption of quality management practices and approaches provides the principles and tools to facilitate the efficient and effective management of the operations of a Service. Therefore, NHSs from developing or developed countries that may not have sufficient funds needed for third-party certification would still greatly benefit by adopting quality management.

The reliability of any water resources assessment will be crucially dependent on the quality of the underlying data. It is therefore important that sufficient emphasis is placed on collecting and collating good quality data that are subject to appropriate checks before they are used in analysis. The degree of checking and verification should take account of the importance of each dataset in the overall assessment. Checks should include consistency in the units of measurement, appropriate allowance for different time periods and spatial scales of measurement and cross-correlation for consistency between different sources.

Harmonization of data

Inevitably, where data are obtained from many different sources there will be significant differences in both quality and presentation. This is particularly important where transboundary data (across national or within country state borders) is involved. Where possible, quality flags should be attached to each data source and carried through the analysis so that it is evident at a later stage if key decisions rely on low-quality data. Where similar data can be correlated and checked from more than one independent source, then clearly the quality status can be raised. Images from different sources (for example, satellite or aerial remote sensing) need to be transformed into a desired coordinate system or the national map projection system for combination with topographic and geologic maps.

Databases and geographical information systems

A Hydrologic Information System is a combination of hydrologic network for data collection, tools for analysis, database for archiving, models that support hydrologic science for producing useful information, appropriate channels for disseminating products and finally training and maintenance. Most hydrometric networks include some form of automated data acquisition, communication, processing (automated, semi-automated and manual processes) and dissemination. This requires the use of specialized software that is dedicated to the business of hydrometric data production. The data management system (software) represents the core element in any Hydrologic Information System.

For many aspects of water resources assessment GIS will provide a valuable tool for analysis, storage of results and presentation. However, whilst standard GIS software is currently good for handling snapshots of spatially varying data fixed in time, it generally has limitations when dealing with time varying data such as precipitation, river flows, groundwater levels and abstractions that are key in water resources assessment. The capabilities of GIS software are being continually improved, but currently standard GIS must be supplemented by tabular data that can be used to provide charts and graphs of trends and variation over time. For some studies relatively simple spreadsheets will be adequate for such data, but more often a comprehensive database will need to be established and this can be complex and demanding to develop and maintain.

CHAPTER 5. PRECIPITATION ANALYSIS

The WMO Commission for Climatology has published guidance material on the collection, preparation and analysis of climatological information, especially precipitation (WMO, 2011). It is recommended that these practices and procedures be adopted in water resources assessment studies.

5.1 ANALYSIS OF TIME-SERIES DATA FOR WATER RESOURCES ASSESSMENT

As noted in Chapter 2, precipitation in all forms is ultimately the primary input to most freshwater systems. In most parts of the world precipitation patterns are highly variable in time and spatial distribution. Reasonable assessment and prediction methods are therefore key to the reliable assessment of water resources. In general, long time series (not less than 30 years) provide the best means to assess current variability and trends but even with longer series care needs to be taken to account for long-term periodical variations (for example, El Niño/La Niña events) (Farquharson and Sutcliffe, 1998), other cyclical phenomena and outlier extremes that, depending on the start and end points of the data series, can have a significant impact on results.

For most water resources assessments daily precipitation gauge readings will be sufficient and most readily available. Ideally these should form a continuous series though this may be impractical, particularly in areas where there is a very clearly defined dry season with no precipitation. Sufficient stations are required to provide a representative sample for each topographic region of the basin (see section 5.5 below).

5.2 MEAN AND VARIATIONS

Mean precipitation is the arithmetically averaged total amount of precipitation recorded during a calendar month or year. The median (decile 5) precipitation is another statistic that is used. From a meteorological point of view the median is usually the preferred measure of “average” or “typical” precipitation. This is because of the high variability of daily precipitation – one extreme precipitation event (such as a slowly moving, severe thunderstorm) will have less effect on the median than it will have on the arithmetic mean. Climate change has called into question the practice of estimating averages over standard periods (often 30 years) as changes and trends now deserve more careful consideration (Sutcliffe, 2004). Simple analysis of a precipitation record provides monthly and annual averages over the period of record (for example, the sum of all January totals divided by the number of years of record provides a figure for the average or mean January precipitation). The maximum, minimum and range or standard deviation can be used to provide a measure of variability for both monthly and annual figures.

5.3 ADJUSTMENT OF SHORT-TERM AVERAGES

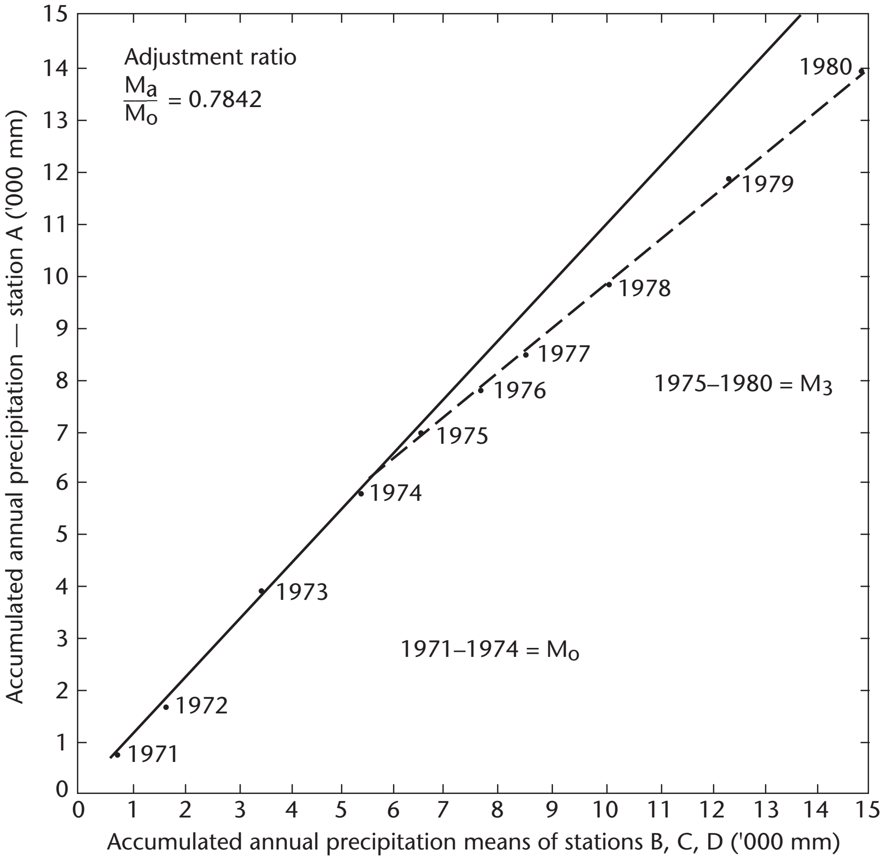
Where records are sparse, it may be necessary to include stations with relatively short records. Longer-term averages can then be estimated by comparing the mean over the common period of record with a topographically similar long-term record and factoring the statistics accordingly. However, such approaches should be used with care and the assumptions made should be taken into account when assessing the reliability of the overall estimate. Chapter 7 provides more detail on gap filling and extension of records for streamflow, some of which can also be applied to precipitation records.

One standard consistency test uses a double mass plot of the accumulated precipitation annual total or seasonal for a given period, plotted against the accumulated precipitation values at a number of surrounding stations (see Figure 5.1). Inconsistency shows up as a change or break in the slope of the line joining the plotted points. Large-scale meteorological changes would not cause a change in slope, as all stations would be similarly affected. Records of different length can be harmonized taking account of these relationships and applying appropriate factors each side of significant changes in slope.

Other approaches such as the simple graphical plotting of cumulative precipitation from a range of similar stations over the same period can enable rapid comparison and draw attention to periods of record where readings may be suspect, owing, for example, to gauge malfunction or other anomalies that warrant further investigation.

5.4 VARIATION OF PRECIPITATION OVER TIME

Since precipitation records are likely to provide the longest available data series for water resources assessment they are the best source for assessing past variations and trends. This can, for example, be achieved by plotting long-term rolling mean values for the period of record and examining the resulting graph. Any known multi-annual cyclical cycles should be taken into account in the choice of rolling average period and it may be necessary to compare several different versions of such plots. Alternatively, trend lines can be fitted to long-term cumulative precipitation plots either by eye or by using mathematical regression programmes.



Source: Guide to Hydrological Practices (WMO-No. 168), sixth edition, page I.9-23

Figure 5.1. 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.

Whatever method is applied, users should be aware that any apparent trend results will always be heavily influenced by more extreme events towards either end of the record, especially if they are relative outliers. Further advice on this topic can be found in WMO (2011).

5.5 ASSESSMENT OF AREAL PRECIPITATION

The accurate estimation of spatially defined daily precipitation is critical to hydrological modelling and water resources assessment. High-resolution precipitation datasets based on gauge precipitation are the primary input to spatially distributed precipitation-runoff models and water balance calculations.

Precipitation

Among the methods used to estimate the mean monthly or mean annual precipitation, two of the most recognized are the isohyets method and Thiessen polygons (Aparicio, 1997). The isohyets method is the more accurate of the two. The method basically entails obtaining curves of equal precipitation, calculating the area between two curves and multiplying it by the average precipitation. The Thiessen polygon method is simpler. It entails obtaining the area of influence of each of the weather stations. By dividing the partial area of the polygon by the total area of the basin, a weighting factor is obtained which, when multiplied by the recorded precipitation at the corresponding station, gives the contribution of that station. The volume of precipitation, per basin, is calculated using the following expression.

$$V_R = P \times A \tag{5.1}$$

where V_R = precipitation expressed volumetrically, m^3; P = mean monthly precipitation, m; and A = basin area, m^2.

With current software packages that have modules on spatial analysis, the following method can be used to quantify the volume of precipitation. The points representing the different weather stations are plotted on a graph. Based on these records, a spatial interpolation is made, obtaining a file similar to a mesh or a rectangular grid (also known as a grid file). Once this file is generated, the assessment of each of the grid cells can be obtained. The user defines the characteristics of the grid and the extension is made to coincide, in this case, with the basin's limits. As the grid is rectangular, a "No data" value is assigned to cells that are outside the basin, and an interpolated value, based on the records of the weather stations, to cells that lie within the basin. The advantage of this method is that there is a better spatial description of the precipitation distribution. By having a precipitation value in each cell, the volume of precipitation is assessed in a simple manner according to the precipitation over a known area equal to the grid size. Therefore, the calculation of precipitation is faster with this option than with Thiessen polygons.

It is important to identify possible gradients in the mean precipitation distribution within the basin, in particular the variation of precipitation with altitude. If possible, several precipitation stations should be used and the areal precipitation computed as a weighted average.

$$P_a = \sum_{i=1}^{n} V_i P_i' \tag{5.2}$$

where P_a = area precipitation; P_i' = "true" point precipitation; V_i = weighting factor for station; and n = number of precipitation stations.

The weighting factors, V_i, can be determined in different ways, for example, Thiessen polygons (Killingtveit, 1985) may be used in a reasonably homogeneous catchment, but a more complex approach may be required where there are significant variations in relief.

There are two further methods that can be easily completed within a GIS framework. Precipitation can be estimated on a grid that covers the catchment using either splines and/or kriging. A spline function is used to fit a mathematical surface to data points such that the curvature of the resulting surface is minimized. Kriging involves fitting a surface based on the weighted sum of the observed data so that the variance of the prediction error is minimized. Both of these methods can be completed within ArcView or the open source software R (R Development Core Team, 2008).

Sources of data other than gauge precipitation, such as satellite-derived fields, radar-based precipitation observations, and climatological fields from numerical weather prediction models, can also be used to either improve the interpolation of gauge data or overcome the absence of gauge records in an area. One globally available product is the Tropical Rainfall Measuring Mission (TRMM) 3B42 satellite-based precipitation product. These data are instantaneous precipitation rates at 0.25° x 0.25° grid resolution time-stamped at three-hourly intervals from which daily precipitation totals can be generated (Renzullo, 2008).

Validating precipitation distribution maps

All resulting precipitation distribution maps should be plotted against backgrounds of topographic and land cover mapping. Topographic comparisons will indicate, for example, areas where the locations of boundaries may need to be manually adjusted to take account of obvious elevation changes or rain shadow areas. Well-informed comparisons with land cover maps can allow the boundaries of some types of precipitation regime to be identified with a high degree of confidence, particularly in semi-arid areas. Abrupt changes in vegetation type will reflect changes in elevation, soil type and precipitation regime that, in the case of some systems, will reflect nature’s accumulated adjustment to water availability over many centuries, certainly more than any human-made recording systems can provide.

Snow and ice

Snowmelt is analogous to precipitation with respect to supply of water for infiltration and runoff, except for the need to account for storage and lag. Precipitation which falls to the Earth’s surface as snow, if kept in the solid state, can form a significant water storage component over months and years in some locations, which is released as runoff, evapotranspiration and groundwater recharge once melted. In the case of temperate areas, storage times in snow cover will typically range from a few hours to a few weeks, and will often have a negligible impact on water resources assessments and can effectively be ignored. However, in high latitudes and mountainous areas, long-term storage in snow fields and glaciers will be a significant factor in long-term water storage, supply and availability.

Rates and distribution of snow can be measured and analysed as for precipitation, provided that records from appropriately adapted gauges are available. Changes in storage over time will usually need to be assessed from repeated aerial or satellite photography, backed up by suitable ground controls and assessments of average pack density with depth. Snow mass can be estimated from snow depth and extent information, then converted to equivalent water volume using a snow density factor (for example, an average value of 0.4 was used by Hennessy et al. (2003)) and remotely sensed hyperspectral data have been used to estimate density to a limited depth. Gridded products such as those generated from MODIS Terra/Aqua and NOAA satellite data are available at a range of spatial and temporal scales and varying accuracy.

Although the distribution and depth of snow cover is mainly dependent on elevation and air temperature, other factors such as latitude, slope, wind exposure and vegetation mean that a simple calculation of snow volume based on elevation and air temperature is too crude to provide a reasonable estimate of snow water volume. Alternative sources of snow depth, coverage and water-equivalent data include snow model output, but these models still require significant input data.

5.6 CHEMICAL COMPOSITION OF PRECIPITATION

Natural precipitation is intrinsically distilled through the evaporative processes that produce atmospheric moisture, and therefore can normally be relied upon to be sufficiently uncontaminated for all human and environmental uses. However, over many heavily industrialized areas, and in considerable areas downwind, the release of gases such as sulphur oxides and nitrogen oxides can result in atmospheric chemical reactions that produce precipitation with significant levels of sulphur and nitric acids. These acids can reduce the pH in natural precipitation from the normal level of 5.6 to levels lower than 4.0 in heavily industrialized areas. Such situations will need to be taken into account when considering effective water availability for a number of sensitive uses.

CHAPTER 6. EVAPORATION

Evaporation or evapotranspiration is used to describe the sum of evaporation and plant transpiration from the Earth's land surface to atmosphere (Dingman, 1994). Evaporation can account for up to 90 per cent of precipitation within drier continents such as Australia. Therefore a detailed understanding of evaporation is profoundly important in the quantification of water resources assessments. Estimation of evaporation relies heavily on model output because of the difficulties of direct measurement and accurate data acquisition.

6.1 POTENTIAL EVAPORATION

Potential evaporation (PE) is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation assuming no limitation in water supply. It is the quantity of water evaporated per unit area, per unit time from an idealized, extensive free water surface under the prevailing atmospheric conditions (Shuttleworth, 1992). The estimation of evaporation at the land surface has long been recognized as the most important process in the determination of the exchanges of energy and mass among hydrosphere, atmosphere and biosphere. Potential evaporation can be used to estimate evaporation from open water bodies and can be attenuated using soil moisture and vegetation cover to estimate actual evaporation (section 6.2).

Evaporation can be determined using direct methods, through measurements with evaporation pans (evaporimeters), or indirect methods using climatic data.

Direct (evaporation pans)

The most common method of estimating evaporation from a free-water body is by using an evaporation pan. The data from evaporation pans can be used to estimate evaporation using the following procedure defined by UNESCO (2008):

1. Identify all the important water bodies using topographic or cartographic maps, satellite images, etc.

2. Associate each water body with a nearby weather station that has records for the corresponding period during which the balance will be made. The selection of each weather station will be related to the quantity and consistency of historical records. If there is more than one station nearby, Thiessen's polygons can be used to obtain average monthly values.

3. Use mean monthly values, obtained from step 2 above and corrected using a coefficient of reduction, to calculate the evaporation in the water body. This coefficient varies within a range of 0.6 to 0.8 (Aparicio, 1997).

4. Finally, multiply the value obtained from step 3 above by the area of the water body. This area is obtained from the information compiled, or is inferred according to the level of the free water surface.

Indirect (climate data)

The Penman formula (Appendix III) can be used if climatic records of daily relative humidity, wind velocity, solar radiation and average temperature are available (UNESCO, 2008). Other indirect methods of estimating PE include Penman–Monteith (FAO 056 Reference potential evapotranspiration), Penpan, Priestly–Taylor, Morton's areal (wet environment) and Thornthwaite (WMO, 2008*a*). There are numerous comparison studies available in the literature; however, most relate to site-specific locations.

6.2 ACTUAL EVAPORATION

As compared with potential evaporation, actual evaporation (AE) is the amount of water that is actually removed from a surface due to the processes of evaporation. Characterization of spatial actual evaporation is required to better constrain catchment-scale water budgets for regional- to national-scale water availability assessments. Information on actual land-surface evaporation can be derived from physical or semi-empirical spatial models of energy balance constrained by satellite and meteorological observations, but the most common way to determine the AE is to solve the water balance.

Remote-sensing data are generally used to derive surface temperature, surface reflectance and vegetation indices, which are combined with local meteorological observations in models to estimate AE. Surface energy balance models are used to estimate the sensible and latent heat fluxes over land surfaces and therefore AE. An example of such a model is the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998*a*, 1998*b*) that uses remote-sensing data in the visible, near-infrared and thermal infrared bands to estimate the energy balance components. A more recent example that uses the globally available MODIS Terra satellite data is the algorithm developed by Guerschman et al. (2009) that uses remotely sensed reflectance data and interpolated climate data.

Water balance method

Actual evaporation from a basin can be estimated as the difference between precipitation (input) and runoff (output) if it can be established by hydrogeological studies that deep seepage is relatively insignificant.

When calculating the annual evaporation the date chosen for the beginning and ending of the water year should coincide with the dry season. The amount of water in storage is relatively small in the dry season and the change in storage from year to year is minimal.

The basic continuity equation for conducting a water balance is presented in UNESCO (2008) as:

$$\frac{dV}{dt} = E - S \tag{6.1}$$

This expresses that variation in volume, V, equals water input (E) minus output (S) for a specific time interval t where actual evaporation is one of the outputs.

A detailed equation of the inputs and outputs of the surface water balance is as follows:

$$\Delta V = (Cp + Ar + Re + Im) - (Ab + U + Ev + Ex) \tag{6.2}$$

where ΔV = variation in volume; Cp = volume of natural runoff through the basin; Ar = volume of upstream runoff; Re = volume of water returns; Im = imports from neighbouring basins; Ab = runoff at basin outlet (downstream); U = water uses; Ev = evaporation in water bodies; and Ex = exports into neighbouring basins.

Depending on the hydrology of the system, assumptions can be made about the terms of the equation. However, where this approach has been taken, analysts need to be aware of the circularity involved in any subsequent water balance calculations (see Chapter 9).

6.3 SOIL MOISTURE BALANCE

Soil moisture storage refers to the amount of water held in the soil at any particular time. The amount of water in the soil depends on soil properties such as soil texture and organic matter content. The maximum amount of water the soil can hold, after gravity drainage, is referred to as field capacity. Fine grain soils have larger field capacities than coarse grain (sandy) soils. Thus, more water is available for evaporation from fine soils than coarse soils. Soil depth is also critical to the total volume of water stored in the soil column. The soil water store can represent a substantial volume and proportion of the available water estimated in a water resources assessment. During drought or long dry periods this store can be significantly depleted requiring several years of above average precipitation to recover.

Soil moisture is measured in situ by a variety of techniques. However, because of the spatial variability of soil moisture, and lack of measurements, such methods cannot be used for the purpose of large-scale soil moisture estimation directly. As ground-based measurement methodologies are impractical, remotely sensed satellite soil-moisture estimates, water balance modelling and assimilation of such remotely sensed (and other climatological observation) data into models are typically employed to estimate soil moisture. These approaches are, however, depth-limited.

An example of a soil moisture estimate produced globally/nationally using assimilation of remotely sensed data and other derived climatological fields is the Global Land Data Assimilation System (GLDAS) project (Rodell et al., 2004), and subsequent refined applications in specific areas and continents. These systems can be used to derive soil moisture estimates by input into hydrological models. An estimate of soil moisture across the continental United States is available at http://hydrology.princeton.edu/~luo/research/FORECAST/current.php.

Apart from the satellite derived methodologies for soil moisture estimation, water balance models (of varying sophistication) can be employed which use only forcing climatological fields such as precipitation and temperature as input. These models typically have a conceptual soil moisture store or series of stores from which runoff and deep drainage is generated depending on forcing input. Spatially varying soil properties are typically required as input to such models.

6.4 ASSESSMENT OF AREAL EVAPORATION

The conventional approach, which assumes that in general evaporation varies quite conservatively over quite large areas, is to evaluate evaporation for each broad land use type in each altitude band (taking account of different wind and radiation exposures, as necessary) and multiply each value by the relevant total area.

However, such conventional techniques that rely on point measurements to estimate the components of energy balance may not take account of the heterogeneity of land surface and the dynamic nature of heat transfer processes. Remote sensing is probably the only technique that can provide representative measurements of several relevant physical parameters at scales from a point to a continent. Techniques using remote-sensing information to estimate atmospheric turbulent fluxes are therefore essential when dealing with processes that cannot be represented by point measurements alone (Su et al., 2003).

Methods using remote-sensing information to estimate heat exchange between land surface and atmosphere can be broadly divided into two categories: to calculate the sensible heat flux first and then to obtain the latent heat flux as the residual of the energy balance equation; or to estimate the relative evaporation by means of an index using a combined equation (Su et al., 2003).

6.5 NET PRECIPITATION

Net precipitation is total precipitation less the interception and evaporation that takes place before the precipitation enters the surface water or soil. It is the basic input into precipitation/runoff modelling for the consideration of both surface water and groundwater resources.

CHAPTER 7. SURFACE WATER

Surface water, generally, lakes, dams, streams and rivers, is water that is open to the atmosphere and feeds by runoff from the surface.

7.1 USE OF GAUGED RIVER FLOW RECORDS

Stream gauging stations provide systematic records of stage and discharge. Continuous streamflow records are necessary to make an accurate water resources assessment. Such records may simply be in the form of manual river level readings once or more per day for large, slow responding rivers, but should ideally come from automatic water level recorders, where river level is recorded at regular time steps onto either a chart recorder or a digital data logger. They are also necessary in the design and operation of water supply and waste systems and in estimating sediment and chemical loads for water quality purposes and for hydropower production.

Naturalizing flow records

Naturalized flow records are primarily those where the effects of historical reservoir storage and evaporation, water supply diversions, and return flows from surface water and groundwater supplies (Warbs, 2006) have been removed. Streamflow records representing historical natural hydrology unaffected by humans are fundamental to modelling basin hydrology. Constructing sequences of monthly naturalized flows for a specified period at gauging stations consists of first adjusting observed flows to reflect natural conditions, and then filling in gaps and extending records. For upper basin sites with relatively undeveloped watersheds, little or no adjustments may be necessary. In extensively developed river basins, quantifying and removing all effects of human activities is not possible.

Many reservoirs, diversions and return flows may be located upstream of the gauging station. If the diversions involve open storage in dams or reservoirs, allowances must also be made for evaporation from these sources. To adjust the flow records to reflect natural conditions at a given gauging station, for a particular month during the historical record, the following equation is solved:

$$NF = GF + \sum D_i - \sum RF_i + \sum EP_i + \sum \Delta S_i \qquad (7.1)$$

where NF = naturalized flow volume; GF = gauged flow; D_i = water supply diversions at locations i upstream of the gauge; RF_i = return flows into the river system at locations i upstream of the gauge; EP_i = volume of evaporation less the proportion of the precipitation volume falling on the reservoir water surface i that would not have reached the stream in the absence of the reservoir; and S_i = storage in upstream reservoirs.

If significant groundwater pumping is occurring within the basin, it may also be necessary to adjust streamflow records to account for reduced discharge from groundwater into stream channels.

Recording of such adjustments is important so that double counting does not take place in subsequent water balance calculations.

Gap filling

Gauge records often do not cover the entire period of analysis. There are several reasons why gaps may occur in streamflow records. Observations may be missing owing to equipment (mechanical, electrical or electronic) failure, effects of extreme natural phenomena such as severe storms or landslides, or of human-induced factors such as wars and civil disturbances, mishandling of observed records by field personnel, or accidental loss of data files in a computer system (Mosley and McKerchar, 1993). Flows during periods of missing data can be determined using regression analyses with flows at other gauges, distribution of flows in proportion to drainage area or by precipitation-runoff modelling.

Regression with nearby gauging station

Regression analysis is used to establish the relationship between an upstream or downstream gauging station with a full dataset and the station with a gap in observations. Both records can be naturalized first, but if the human influence is similar for both stations this is not always necessary. The type and extent of human influence may differ between stations. Judgment is required in selecting gauges and incremental watersheds for synthesizing flows at ungauged sites. The watershed associated with the incremental or total flows at the source gauge should have similar characteristics as the watershed of the ungauged site (Warbs, 2006). Neural networks can also be used to establish relationships between gauging stations for the purpose of filling gaps or extending records, but regression is the most common method.

It can also be useful to plot hydrographs of daily discharges of the incomplete record, as this can indicate typical rates of recession between storm and precipitation events. These hydrographs can be used with other evidence such as precipitation records and concurrent hydrographs from other streams.

Drainage area ratio method

The drainage area ratio (DAR) method distributes flows in proportion to drainage area (DA).

$$Q_{ungauged} = R_{DA} Q_{gauged} \tag{7.2}$$

$$R_{DA} = \frac{DA_{ungauged}}{DA_{gauged}} \tag{7.3}$$

$$Q_{ungauged} = R_{DA}\,(Q_{gauged} + F_{CL} Q_{ungauged}) \tag{7.4}$$

The following equation may optionally be applied in situations where the ungauged site is located upstream of the gauged site with channel losses (CL) occurring between the sites at rates that are significantly greater than the loss rates in the watershed above the ungauged site.

$$Q_{ungauged} = Q_{gauged}\left(\frac{R_{DA}}{1 - R_{DA} F_{CL}}\right) \tag{7.5}$$

where F_{CL} is the fraction of channel loss above the ungauged site.

Precipitation-runoff models

If streamflow data are unavailable or are too limited for reliable interpretation or extrapolation, precipitation-runoff relationships can be used to extract streamflow information from the precipitation records. A range of suitable models is available, such as HYSIM,[17] TOPMODEL[18] or HYRROM,[19] although the software was originally produced and sold by the United Kingdom Centre for Ecology and Hydrology (CEH)[20] IHACRES[21] and similar products. Alternatively, a

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[17] http://www.watres.com/software/HYSIM/info.html

[18] http://www.es.lancs.ac.uk/hfdg/freeware/hfdg_freeware_top.htm

[19] http://www.mpassociates.gr/software/environment/hyrrom.html

[20] http://www.ceh.ac.uk/products/software/water.html

[21] http://www.ceh.ac.uk/products/software/CEHSoftware-PC-IHACRES.htm

simplified approach such as the Natural Resource Conservation Service (NRCS) curve number method may be used. The procedure for determining the runoff volume calculation using the NRCS curve number (NRCS, 1985) is provided in Appendix IV.

Extension of short records

The methods used in the extension of short streamflow records are similar to those used to fill gaps in records. Where flow records are shorter than required, it may be possible to assess the reliability of shorter records by relating them to the equivalent periods of longer records at other stations in the region. Thus, if station A has a record of only 15 years, and a mean annual runoff from this period of Q_A million m^3, and a longer record at station B has a long-term record over, say, 40 years with a mean annual runoff of $Q_{B(40)}$ million m^3, the mean annual flow at station A may be adjusted by:

$$Q_{Aadj} = Q_A * Q_{B(15)}/Q_{B(40)} \tag{7.6}$$

where Q_{Aadj} is a more reliable adjusted estimate of the long-term mean annual runoff at site A; $Q_{B(15)}$ is the mean annual runoff at site B for the same 15-year period of record as site A; and $Q_{B(40)}$ is the longer term 40-year mean annual runoff at site B. Thus, if the 15-year concurrent period is wetter or drier than the long-term mean at site B, the recorded mean annual runoff at site A will be adjusted to reflect the non-representativeness of this 15-year period.

Precipitation-runoff models

Alternatively, short river flow records may be extended through precipitation-runoff modelling using longer-term precipitation records in the same way as for gap filling. In general, precipitation records are longer than the equivalent river flow records, as precipitation is easier to collect and is more widely available.

Regression models

Short flow records may be extended through regression with nearby flow stations having longer records, provided the donor catchment has similar climate and hydrological characteristics to the site of interest. Simple or multiple linear regressions are most commonly applied for transferring hydrologic information between two gauging stations. A simple linear regression model that may be established to extend the short record y_t is:

$$y_t = a + bx_t + \alpha\theta\left(1-\rho^2\right)^{1/2}\sigma_y\varepsilon_t \tag{7.7}$$

where y_t = dependent variable (short record); x_t = independent variable (long record); a, b = population parameters of the regression; α = coefficient; $\theta = 1$ when noise ε_t is added; $\theta = 0$ when ε_t is not added; ρ = population cross-correlation coefficient between y_t and x_t; σ_y = population standard deviation of y_t; and ε_t = normal uncorrelated variable with mean 0 and variance 1 which is uncorrelated with x_t.

And a multiple regression might be:

$$y_t = a + \sum_{i=1}^{m} b_i x_t^{(i)} + \alpha\theta\left(1-R^2\right)^{1/2}\sigma_y\varepsilon_t \tag{7.8}$$

where a and b are estimated by:

$$\hat{a} = \overline{y}_1 - \sum_{i=1}^{m}\hat{b}_i\overline{x}_1^{(i)} \tag{7.9}$$

$$\hat{b}_i = \sum_{j=1}^{m}\hat{d}_1^{(ij)}\hat{c}_1^{(i)} \tag{7.10}$$

7.2 INTERPRETATION OF RIVER FLOW RECORDS

Hydrograph separation

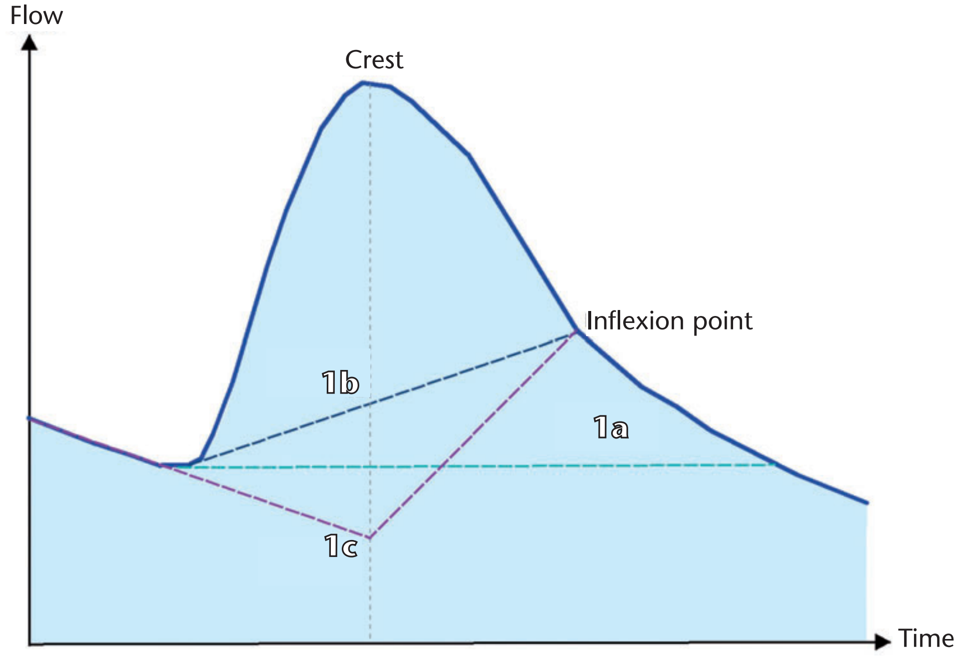
Separation of streamflow hydrographs into base-flow and surface-runoff components is used to estimate the groundwater contribution to streamflow. Base flow is the relatively slowly varying component of streamflow and is frequently the result of the discharge of groundwater to wetlands, lakes and rivers. Hydrograph-separation techniques have also been used to quantify the groundwater component of hydrologic budgets and to aid in the estimation of recharge rates. In addition, base-flow characteristics determined by hydrograph separation of hydrographs from streams draining different geologic terrains have been used to show the effect of geology on base flow (Sloto and Crouse, 1996).

Streamflow monitoring information, typically daily average data, and computational methods of base-flow separation are often used to estimate base flow. The monitoring information and related parameters, such as drainage area, are input into base-flow separation algorithms, which calculate an output time series of base flow that can then be summarized on a monthly, seasonal, annual or length-of-record basis (Piggott et al., 2005).

Techniques of hydrograph separation (Figure 7.1)

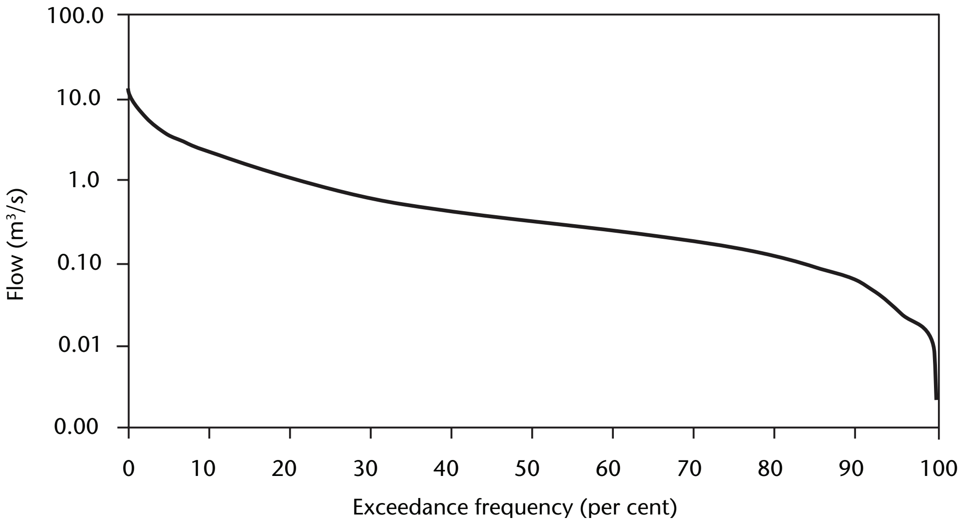
United Kingdom base-flow index method

The United Kingdom Centre for Ecology & Hydrology method is based on the identification and interpolation of turning points within an input time series of streamflow monitoring information. The method is applied to daily average data; however, higher frequency data can be aggregated on a daily basis and then processed using the method. The turning points indicate the days and corresponding values of streamflow where the observed flow is assumed to be entirely base flow. To calculate the points, the streamflow data are partitioned into a sequence of five-day segments and the minimum values of streamflow within each segment, an x and y pair where x_i is the day on which the minimum value of flow of y_i occurred, are selected and defined as candidate turning



Source: http://adl.brs.gov.au/brsShop/data/iah05_baseflow_final.pdf

Figure 7.1. Graphical baseflow separation techniques including (1a) constant discharge method, (1b) constant slope method and (1c) concave method (Linsley et al., 1982)



Source: Manual on Low-flow Estimation and Prediction (Operational Hydrology Report No. 50, WMO-No. 1029), page 50

Figure 7.2. Flow duration curve for the Drammenselv at Fiskum in Norway

points. Each candidate is then compared with the minima for the previous and subsequent segments. Turning points are defined where the condition $0.9y_i < \min(y_{i-1}, y_{i+1})$ is satisfied. This process results in an irregular sequence of turning points. The temporal variation of base flow is estimated by piecewise linear interpolation bracketed by successive pairs of turning points. A daily time series of base flow can be calculated by applying this interpolation to the timing of the input streamflow data and total volumes of base flow can be calculated by integration of the interpolation (Piggott et al., 2005).

7.3 ESTIMATION OF MEAN ANNUAL FLOW AND VARIABILITY

Flow duration curves

A flow duration curve (FDC) is an expression of frequency of occurrence; it is constructed from gauged flow data by ranking flows in decreasing order of size and plotting flows as functions of exceedance probability (Figure 7.2). Flow duration curves are often used to determine trigger points for limits on abstraction or introduction of water conservation measures. They provide a summary of flow data that shows the percentage of time a given flow is equalled or exceeded. A log-normal transformation for the flow data is normally applied to linearize the resultant curve (Holmes et al., 2002*a*, 2002*b*).

Flow duration curves are among the most useful and widely used methods of summarizing a time series of flows. They can be based on daily, monthly or annual flows and constructed for periods of interest such as whole year, seasons, and high or low-flow periods. They may use the whole period of record or parts of the record to analyse variability. Flow duration curves can be used as part of yield assessment, to guide planning of sustainable diversions from rivers, as part of drought planning, to provide input to studies of hydropower and river and reservoir sedimentation, and to facilitate scientific comparisons of streamflow characteristics across catchments (Ladson, 2008). Flow duration curves have long been used as means of summarizing catchment hydrologic response, but more recently they been used to test the outputs of hydrologic models and/or compare observed and modelled hydrologic response (Post, 2004).

The procedure used to prepare a duration curve is as follows:

1. The total range of discharge is divided into a number of classes. For example, the discharge ranging from 0 to 100 m^3/s could be divided into 20 classes of 5 m^3/s each.

2. The entire record is scanned day by day for daily flows, month by month for monthly flows, and year by year for yearly flow curves.

3. A mark is made in the appropriate class for each item in the record. The plot of the number of items in each class against the discharge value of the class will represent the frequency distribution.

4. The number of items in each class is accumulated starting with the highest flow. The per cent of the accumulated number of items of each class with respect to total items of all classes is determined.

5. The average discharge value of each class is plotted on the vertical scale against the per cent (of time) determined in step 4.

It is possible to produce a non-dimensional flow duration curve by dividing by the mean appropriate for the chosen time base. This allows flow duration curves to be compared between catchments (Ladson, 2008).

Flow duration curves can be constructed in Excel using the percentile function. For example, if a daily flow duration curve is required, the cells containing the daily flows are used as the array; k values in the Excel percentile function, defined from 0.95 to 0.05 at increments of 0.05, will specify 19 points on the flow duration curve (Ladson, 2008).

The shape of the standardized flow duration curve indicates the characteristic response of a catchment to precipitation. High gradient curves reflect a very variable flow regime; low storage of water in the catchment results in a quick response to precipitation and low flows in the absence of precipitation. A steep section near the low-flow end of the flow duration curve suggests there is little groundwater input, base flow is insignificant and the stream dries up rapidly once rain ceases. A steep area at the top of a curve suggests that there are a small number of high-flow events that produce flows a lot higher than those that occur most of the time. Low gradient flow duration curves indicate that the variance of daily flows is low, because of the damping effects of naturally provided groundwater storages (Holmes et al., 2002*a*, 2002*b*).

Ungauged basins

In many cases it will be necessary to estimate surface flow for catchments where no gauged records are available. The techniques described in section 7.1 for gap filling and record extension can be applied in principle though with a significantly greater range of uncertainty. Where possible pooled data, for catchment characteristics from a range of gauged catchments that are hydrologically and geologically similar, can be applied to appropriate catchment models. In general, estimates will be improved if a larger donor group is used, but it may be necessary to weight the data to take account of the different degrees of catchment similarity.

Multivariate linear regression analysis is the most widely used statistical technique for developing these models or rules for a region. Linear regression is a special case of Generalized Linear Models (GLM); these methods are valid only over the range of dataset used to construct the models. More sophisticated models involve ascribing a probability distribution to the dependent variable, in this case a flow statistic. Some function, known as the link function of the distribution parameters, is then modelled as a linear combination of the independent predictor variables. GLM-based techniques for estimating flow statistics have been used widely in the United States of America (Holmes et al., 2002*a*, 2002*b*).

Low flows can be computed for an ungauged basin by applying a drainage area ratio adjustment method using low-flow rates of a nearby gauged basin (USGS, 2002). Low flows can also be estimated using regional regression models (Flippo, 1982; Zhu and Day, 2009).

Whatever approach is adopted, developing sequences of flows for ungauged basins necessarily involves uncertainties and inaccuracies that are greater than for gauged basins, including the following:

(a) Precipitation, streamflow and other hydrologic parameters are highly variable both temporally and spatially;

(b) Watersheds may be highly non-homogeneous with soils, vegetation, land use, topography and other characteristics changing significantly over short distances;

(c) Watershed characteristics are difficult to accurately measure;

(d) Changes over time in land use and other watershed characteristics are typically not reflected in the process of naturalizing gauged flows;

(e) The hydrologic processes that transform precipitation to streamflow, such as infiltration, surface storage–flow, subsurface storage–flow and evapotranspiration, are complex;

(f) Interactions between subsurface flows and streamflows are complex, for example, in terms of groundwater recharge and areas where subsurface flow can rejoin the surface flow and enter into streams;

(g) Inaccuracies are inherent in all recorded data including gauged streamflows and the historical reservoir and water-use data used to convert gauged flows to naturalized flows. (Warbs, 2006)

Catchment yield

Catchment yield is generally expressed in terms of cumulative catchment runoff as a depth in mm rather than as a volume or mean flow rate. This allows direct comparison with precipitation statistics such as cumulative monthly or annual precipitation and a rapid appreciation of overall catchment “losses”.

7.4 PROBABILITY ANALYSIS

As most of the climate processes and many of the catchment responses driving hydrology can be considered to have significant random elements, it is not possible to provide deterministic answers in water resources assessment so results can usefully be presented in probabilistic terms. A probabilistic approach is required in order to incorporate the effects of random variations in drivers and responses into decision-making. If the occurrences can be assumed to be independent in time, that is, the timing and magnitude of an event bears no relation to preceding events, then frequency analysis can be used to describe the likelihood of any one or a combination of events over the time horizon of a decision. Interactions between different variables can be analysed in probabilistic terms using techniques such as Monte Carlo analysis. Where such variables are not independent, then joint probability techniques need to be employed.

The presentation of probabilistic results and the related uncertainties to non-specialists, including decision-makers and the general public, is a challenge and care needs to be taken to avoid misunderstanding of technical terms such as risk and probability.

Low-flow frequency analysis

Low-flow frequency analysis is the process of determining the probability of different periods of low flow. The initial data required are a long series, usually 30 years or more, of daily flow. The series may be recorded data, synthesized historical data from other sources such as precipitation records and catchment modelling, or a synthesized series of future data based on climate and catchment changes.

From the daily data a rolling total flow figure is calculated for the desired time period, so for a seven-day minimum flow the total for each seven-day period is calculated. The lowest flows in each hydrological year can then be ranked. For low-flow analysis purposes, the hydrological year should be defined such that low-flow periods generally occur in the middle of the year; therefore, in the northern hemisphere it is common to use calendar years starting on 1 January but in the southern hemisphere years starting on 1 July or 1 August are usually more appropriate.

Separate analyses are generally undertaken to produce probability plots for 1-day, 7-day, 15-day and 30-day low flows, but longer periods may also be required, particularly where there are regular prolonged dry seasons. Low-flow data are generally plotted with a logarithmic scale for the ordinate and an extreme-value probability scale as the abscissa so that a straight line can be fitted to extend the range of probability. Alternatively, parameters can be fitted to an extreme value distribution, such as Weibull.[22] It is then possible to infer the 1 in 10 (10 per cent), 1 in 50 (2 per cent), and so forth, annual probability of the N-day low flow.

Low-flow frequency analysis can also be applied on a regional basis to pooled groups of catchments that are hydrologically similar. This can significantly improve the confidence in extreme estimates, particularly where individual catchment records are relatively short. For the purpose of regional analysis, extreme distributions between catchments have to be normalized and this is often achieved by dividing flow values for each catchment by the mean low flow for that catchment. Distributions for ungauged catchments can then be obtained if the mean low flow can be estimated by regression analysis.

See, for example, Nathan and McMahon (1990) and WMO (2008*a*) for more detailed guidance on practical low-flow frequency analysis.

Flood frequency analysis

Flood frequency analysis for the design of hydraulic structures and flood damage mitigation is outside the scope of this publication. Advice on flood frequency analysis techniques can be found in WMO (2008*a*). The main concern for water resources assessment is to determine the extent to which flood waters can be captured for subsequent use or resource augmentation (for example, using techniques of managed aquifer recharge) and the overall volume of flood runoff that will effectively be lost from annual precipitation totals, because it is not realistic or feasible to provide storage in the river basin. Whilst reliable estimation of extreme floods is very significant for the design of safe reservoirs and other structures, the rarest and most extreme events are unlikely to have any significant impact on long-term water balance and therefore can be ignored for water resources assessments.

Generally, a relatively simple “peaks over threshold” approach will be sufficient to estimate losses to the annual water balance from direct flood runoff. The method involves the examination of historical river flow records and the extraction of all flows above a chosen threshold. If this threshold is chosen to be analogous to the point at which most catchment storage is filled, then the annual average summed flows above this level will provide a first-order estimate of flood runoff losses.

In considering long-term resource assessments, any change in precipitation patterns may change the nature and frequency of flood runoff losses, as will any significant changes in catchment storage. These should generally be considered by adjusting the historical analysis or incorporating such changes in long-term simulation modelling.

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[22] http://www.mathworks.ch/ch/help/stats/wblpdf.html

7.5 STORAGE IN NATURAL LAKES

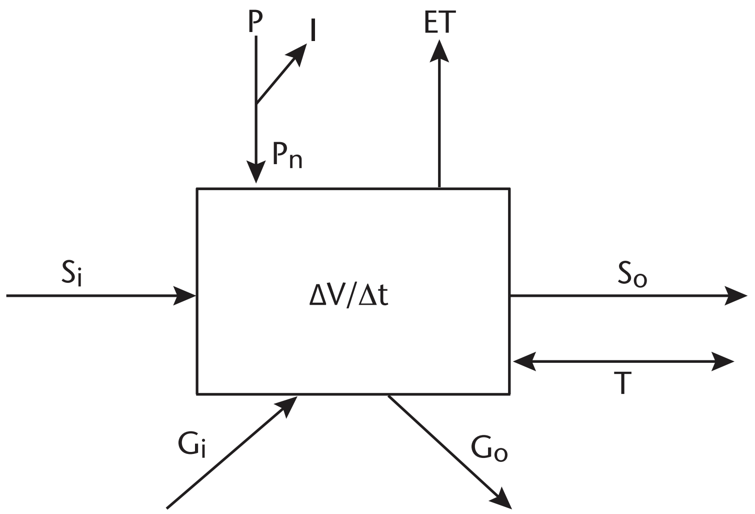
For many natural lakes it will be sufficient to monitor changes in level and simply multiply by the surface area to estimate change in volume. For greater accuracy contour plots of the banks should be obtained so that a depth/storage relationship can be established. In many cases the outflow from a lake will be determined by some form of hydraulic structure, whether a rock ledge acting as a weir or a constricted channel. Knowledge of the channel features that control the stage-discharge relation is therefore a crucial component in developing rating curves. The outflow/level relationship can then be established by approximating the physical characteristics of the hydraulic controls. In accounting for changes in lake storage, any outflow to groundwater recharge from the lake bed (usually small) or lake margins should be considered, as should the open water evaporation from the lake surface (Finch and Calver, 2008).

7.6 WETLANDS

Wetlands regulate the movement of water within watersheds. They store precipitation and surface water and then slowly release the water into associated surface water resources, groundwater and the atmosphere. Wetlands, by definition, are characterized by water saturation in the root zone, at or above the soil surface, for a certain amount of time during the year. The water balance of wetlands is summarized in Figure 7.3.

Wetlands help maintain and improve the water quality of streams, rivers, lakes and estuaries. They intercept and process runoff water before it reaches downstream water resources by removing and transforming pollutants such as phosphorus, nitrogen and metals. Sediment deposition in wetlands also prevents a source of turbidity from entering downstream ecosystems. Typically wetland vegetation traps 80–90 per cent of sediment from runoff (Gilliam, 1994; Johnston, 1991). Wetlands help protect adjacent and downstream areas from potential flood damage and by virtue of their place in the landscape, riparian wetlands, located at the margin of streams and lakes, protect shorelines and stream banks against erosion.

The magnitude of evaporation loss from wetlands is generally higher than from open water but is dependent on the local environment of the site. The higher evaporation losses can be due to the greater surface area of the vegetation, larger aerodynamic roughness and the limited stomatal control of the plants (Robinson et al., 1991). The magnitude of evaporation can also be influenced by local advection conditions.



P	Precipitation
P_n	Net precipitation
ET	Evapotranspiration
I	Interception
S_i	Surface water inflow
S_o	Surface water outflow
G_i	Groundwater inflow
G_o	Groundwater outflow
T	Tide
V	Storage volume
t	Time

Source: Mitsch and Gosselink, 2000

Figure 7.3. Wetland water balance

Areal extent of wetlands

Remote sensing provides cost- and time-effective data on the areal extent of wetlands. It offers techniques that enable rapid acquisition of data with a generally short turn-around time, at a cost lower than that of ground surveys (Castañeda et al., 2005). These advantages make remote sensing ideal for use in delineating the fluctuating margins of shallow-water systems such as wetlands where several assessments might be needed to obtain an average estimation of extent.

In the past aerial photography served the purpose of identification, delineation and measurement of spatial extent of wetlands. But with the launch of remote-sensing satellites such as the Landsat series with Multispectral Scanner (MSS) and later Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+), it has become possible to capture multi-date digital images over a greater array of spatial and temporal scales than was possible with aerial photography. Landsat-TM provides data with a spatial resolution of 30 metres, making it an especially valuable tool for studying smaller wetlands. The long history of the Landsat series also makes it possible to conduct analysis of the change in wetland extent over a 30-year period. Rebelo et al. (2009) used multispectral Landsat satellite imagery from 1992 to 2002 to capture spatial changes in the land cover and land use observed in the wetlands and adjacent land on the west coast of Sri Lanka. All types of wetlands have been studied with satellite remote sensing. Landsat MSS, Landsat TM and SPOT are the major satellite systems that have been used to study wetlands; other systems are NOAA AVHRR and IRS-1B LISS-II. The high temporal resolution data sources (Appendix II) provide opportunities to quantify the seasonal variation in wetland water resources, but care must be taken in longer term records to assess the wetland extent at the same time each year to avoid discrepancies in the record.

Wetland classification

Early work with satellite imagery used visual interpretation for classification, but current multispectral and hyperspectral data provide the ability to conduct automated classification of land cover (O’Hara, 2001). The most commonly used computer classification method to map wetlands is unsupervised classification or clustering, but supervised maximum likelihood algorithms have also been used.

Wetland classification is difficult because of spectral confusion with other land cover classes and among different types of wetlands. However, multi-temporal data usually improve the classification of wetlands, as does ancillary data such as soil, elevation or topographic data (Ozesmi and Bauer, 2002; Rebelo et al., 2009). For example, where mature forest is present, the spectral signatures of wetland vegetation or water may be obscured by the forest canopy. Thus, in these areas, the spectral signature of high spatial and spectral resolution remotely sensed image data alone cannot accomplish evaluation of water, wetland and associated vegetation. Spectral analysis must be accompanied by data fusion techniques that analyse the combined information products of spectral analysis with elevation data derived topographic and hydrologic information products such as flow accumulation, topographic depressions and topographic slope. LIDAR-based digital elevation data can be used to create data layers related to hydrologic conditions including filled hydrologic surface, hydrologic sinks surface and other hydrologic data derivatives such as flow direction and flow accumulation. O’Hara (2001) provides a comprehensive review of the use of ancillary data in wetland classification.

Links to groundwater

Wetlands are often intermediate points between surface water and groundwater, making them an integral point of assessment when identifying the links between groundwater and surface water, one of the most difficult aspects of the hydrological cycle to assess in a WRA. Wetlands facilitate the flow of water between the groundwater system and surface water system. The relationship of the groundwater table and the land surface dictates which function – groundwater recharge or discharge – a wetland performs.

The relationship between groundwater and wetland hydrology is a balance. The drainage of wetlands lowers the water table and reduces the hydraulic head, providing the force for groundwater discharge. If a recharge wetland is drained, the water resources into which groundwater discharges will receive less inflow, potentially changing the hydrology of a watershed. The extent of groundwater recharge by a wetland is dependent upon soil, vegetation, site, perimeter to volume ratio and water-table gradient. Groundwater recharge occurs through soils found primarily around the edges of wetlands as the soil under most wetlands is relatively impermeable. A high perimeter to volume ratio, such as in small wetlands, therefore provides a greater surface area through which water can infiltrate (Turner and Gannon, 1995). Wetlands can contribute up to 20 per cent of their volume to groundwater each season (Weller, 1981).

Landscape position affects the amount and source of water in a wetland and hence its relationship with local surface water and groundwater resources. Wetlands can be precipitation dominated, groundwater dominated or surface flow dominated. Precipitation-dominated wetlands are commonly in elevated positions in the landscape where they receive little or no surface runoff or discharge from groundwater. These wetlands generally have a clay or peat layer that retains the precipitation and limits discharge to groundwater. Groundwater-dominated wetlands form in lower points in the landscape such as valley floors and at the base of hills where groundwater actively discharges. These wetlands may also receive overland flow, but they receive a steady flow of water from groundwater sources. However, most wetlands at low points in the landscape are dominated by inflow from surface water sources. These wetlands will actively recharge groundwater resources. Turner and Gannon (1995) provide a comprehensive review of the role of wetlands in the hydrological cycle.

7.7 SURFACE WATER QUALITY

In addition to focusing on volumes or quantities of water, water quality is used to assess the usability of that water for a particular purpose, whether for human consumption, agricultural production, industry or the needs of the environment. In addressing issues of water quality, it is essential to have an understanding of the criteria (maximum allowable concentrations) for the main indicators of water quality and how they relate to the particular use to which the water will be put, for example, for domestic water supply versus for stock water supply.

Physiochemical parameters

The overall water quality of a water body is assessed by collecting data from a range of physiochemical parameters. Some of the core physiochemical parameters that are frequently used for water quality assessments are listed below. This is by no means an exhaustive list, and the range and number of parameters monitored will generally be related to available equipment, the purpose of the assessment and the cost of testing.

Water temperature

Water temperature has a direct relationship with other physical and chemical parameters, in that photosynthesis and decomposition increase at higher temperatures. The solubility of salts increases as temperature increases, whereas less oxygen is soluble at higher temperatures.

The metabolic rate of aquatic organisms is also dependent on temperature, and species have evolved to live within specific temperature ranges. Survivability of aquatic organisms can be compromised if the temperature range extends outside their tolerance range. Acute (short-term) changes in temperature may cause mortality, whereas chronic (long-term) change can affect the suite of species that are present in an ecosystem.

Factors that influence water temperature include air temperature, exposure to sunlight, turbidity, groundwater inflows, industrial discharges/thermal pollution, cold water from dams, vegetation, and the type, depth and flow of a water body.

pH (acidity)

Acidity (pH) is the measure of the activity of hydrogen ions (H^+) in a solution, which indicates how acidic or alkaline the solution is. Values of pH range between 0 (highly acidic) to 14 (highly alkaline). A neutral solution, which has no net acidity or alkalinity, has a pH of 7. Pure water is a neutral solution.

It is important to recognize that pH is an inverse logarithmic scale, and a one-unit increase actually represents a 10-fold increase in acidity. For example, if a water sample decreases from pH 7 to pH 6, there has been a tenfold increase in the number of H^+ ions in the solution. If a sample decreases from pH 7 to pH 5, there has been a 100-fold increase in the number of H^+ ions in the solution.

Plants and animals are adapted to specific pH ranges (generally 6.5 to 8.0). A change in pH extending outside of the normal range can cause stress and/or mortality in the aquatic community.

Factors that influence the pH of a water body include the source of water, precipitation, photosynthesis and respiration, water temperature, plant growth in the water, geology and soils, industrial discharge, atmospheric deposition and salinity.

Conductivity and salinity

The terms conductivity and salinity are sometimes used interchangeably although they have different meanings. Salinity is the measurement of how much salt is dissolved in water, whereas electrical conductivity (EC) is a measure of the ability of the water to conduct electricity (most commonly measured in the field). As the ability of a water sample to conduct electricity is based on the amount of salts dissolved in the water, conductivity is commonly used as a surrogate measurement of salinity.

Whilst higher conductivity generally means that the water sample has a higher salinity, it is important to recognize that the solubility of salts is determined by water temperature, and so corrections may need to be made to account for this.

The types of dissolved salts in water bodies that contribute to conductivity are sodium, chlorides, sulphates, carbonates, magnesium, calcium and potassium.

Plants and animals are adapted to a specific salinity, ranging from fresh to hyper saline. A change in salinity extending outside of the normal range can cause stress and/or mortality in the aquatic community.

Factors that influence conductivity include geology and soils, surrounding land uses (agriculture, urban development, land clearing, industrial development, and so forth), flow, runoff, groundwater inflows, temperature, and evaporation and dilution.

Turbidity

Turbidity is a measure of how much material (silt, sand, clay, algae, plankton, and so forth) is suspended in the water column, or conversely, how “clear” the water column is. This in turn affects how far light can penetrate into the water. High turbidity means more suspended material and less light penetration.

Greater suspended materials also cause the water body to absorb more heat, affecting the temperature properties of the water, which has a direct relationship with dissolved oxygen and salinity.

Plant growth is particularly affected by turbidity, as reduction in light penetration into the water causes much reduced photosynthesis. A secondary effect is the reduction of habitat, food and oxygen that plants provide for aquatic animals. This also has a direct impact on fish as, for example, suspended material can clog gills, which has potential to cause stress and/or mortality.

Factors that influence turbidity include precipitation and catchment runoff, soil erosion, bed disturbance (for example, introduced fish species), waste discharge, storm water, algal blooms, riparian vegetation, floodplain and wetland retention and deposition, flow, soil types, waterway structure and salinity.

Dissolved oxygen

Dissolved oxygen (DO) is a measure of how much oxygen is present in the water and available for use by plants, animals and bacteria.

Plants and animals require oxygen for respiration, therefore, low concentrations of DO can cause stress and/or mortality. Very high, or "supersaturated", DO can also be harmful to aquatic animals, particularly fish.

Factors that affect the concentration of DO in the water body include diffusion from the atmosphere, flow, turbulence, water depth, type of water body, time of day, photosynthesis and respiration, salinity, altitude, seasonal fluctuations, breakdown of organic materials and temperature.

Biological oxygen demand

Biological oxygen demand (BOD) is a measurement of how quickly organic substances use up the dissolved oxygen during the biochemical oxygenation processes in a water body, which is an indirect indication of how much organic matter is in the water body.

Pristine waters have very low BOD, and polluted waters or water bodies with sewage or industrial discharge have a high BOD.

Factors that influence the BOD of a water body include vegetation, and municipal, industrial and sewage discharges.

Nitrate (NO_3)

Nitrate is a measure of the concentration of the element nitrogen in the water body that is available for use by aquatic plants and animals.

Plants and animals require nitrogen as a source of nutrients, and it is continually recycled by them in the water body. Plant growth requires both nitrates and phosphates as a source of nutrients. In general, the concentration of nitrogen is higher than phosphates in freshwater systems, therefore making it a "phosphate limiting" system. Conversely, in general, the concentration of nitrogen is lower than phosphate in saltwater systems, therefore making it a "nitrogen limiting" system.

Factors that affect nitrogen concentration in the water body include underlying geology, soil type, vegetation, seasonal fluctuations, sewage discharge, organic decomposition, industrial discharge, runoff and nitrogen-based fertilizers.

Phosphate (PO_4)

Phosphate is a measure of the concentration of the element phosphorus in the water body that is available for use by aquatic plants and animals.

Plants and animals require phosphates as a source of nutrients. Freshwater systems generally have low concentrations of phosphate compared to nitrogen, and so a sudden increase can cause rapid increase in algae and other aquatic plants. Some algal blooms (such as blue-green algae) can produce toxins and cause large reductions in DO and increased turbidity.

Table 7.1. Examples of monitoring parameters to determine ecological status of a water body

Element	*Parameters to be monitored*
Biological	Phytoplankton Macrophytes Algae Angiosperms Benthic invertebrate fauna Fish fauna
Hydromorphological	Tidal regime Hydrological regime River continuity Morphological conditions
Physico-chemical	General water quality (temperature, pH, DO, EC, turbidity, etc.) Specific synthetic pollutants Specific non-synthetic pollutants

Factors that affect the concentration of phosphates in a water body include underlying geology, soil type, seasonal fluctuations, sewage, phosphate-based fertilizers, disturbed land and urban storm-water runoff.

Pesticides and herbicides

Pesticides and herbicides are substances that are used to control insects, weeds and diseases that affect agricultural productivity. There are far too many pesticides to list here; local agricultural authorities should be contacted for more information on specific pesticide and herbicide use in the study area. Both are considered as poisons, and can have detrimental effects on plants and animals, not only within the water body but also others that use the water body as a resource, including humans.

Pesticides and herbicides are normally associated with agricultural activities. However, there are a number of factors that can affect how they get into water bodies, including runoff, persistence (the rate of degradation of the pesticide), water solubility and agricultural application methods.

Ecological status

Ecological status refers to the quality of the structure and functioning of aquatic ecosystems, and is determined by monitoring biological, hydro-morphological and physiochemical elements.

The primary focus is on the biological element of the water body, while hydromorphological and physiochemical elements are used to support the biological element. To address each of the elements, it is suggested that one or more parameters are monitored. Examples of some of the suggested parameters to be monitored are shown in Table 7.1.

The ecological status concept is expected to continually evolve over the next decade as it is implemented in the European Union (EU) though its Water Framework Directive (WFD) and the Common Implementation Strategy (CIS). More detailed and up-to-date information on how ecological status is being used in this regard is available on the EUROPA European Union website http://ec.europa.eu/environment/water/index_en.htm (River Basin Management menu). The WFD legislation and detailed guidance documents are very good background reading and can be found at http://circa.europa.eu/Public/irc/env/wfd/library in the relevant folders. It should be noted that the WFD is a very ambitious and demanding piece of legislation and its application outside the EU needs to be considered carefully.

CHAPTER 8. GROUNDWATER

Groundwater is water that occurs below the surface of the Earth, where it occupies spaces in soils or geologic strata. Most groundwater comes from precipitation, which gradually percolates into the Earth.

8.1 GROUNDWATER OCCURRENCE

Groundwater is much more difficult to detect and characterize than surface water. Springs and vegetation species can give some clues, but generally, the spatial distribution of groundwater occurrence needs to be assessed through an evaluation of geological, hydrogeological, hydrological and climatological conditions. It is not an easy task because these conditions may vary over short distances.

Geological conditions

The general pattern of groundwater occurrence on a river basin level can be obtained by dividing the area into regions, based on the dominant geological settings, as follows:

- *Basement regions*. In these regions, geologically very old (usually Precambrian) crystalline rock occurs at or near the surface. In large parts of these regions, groundwater is only present at shallow depths, often in fractures or weathered zones in the consolidated rocks. Stored volumes of groundwater are limited.

- *Sedimentary basin regions*. These regions are characterized by thick and extensive sedimentary layers that may be permeable to a considerable depth. Consequently, they may form huge reservoirs and the largest groundwater reserves on Earth are to be found in these regions.

- *Volcanic regions*. Occurrence of groundwater in these regions is affected by relatively recent (Tertiary and Quaternary) volcanism. Groundwater occurs in porous or fractured lavas and in sediments interbedded between lava flows. Highly permeable zones are not exceptional.

- *High-relief, folded mountain regions*. In these regions, various types of rocks are arranged in complex structures. Inside the folded rocks, occurrence of groundwater is fragmented. Good aquifer zones are often found in alluvial deposits in valleys and plains.

Information necessary for the above division can be obtained from geological reports and maps (seen section 4.2.3).

For local studies, specific information on lithology and structure of various geological formations occurring in the study area is required. Delineation of lithostratigraphical units and identification of structural features (for example, faults) lead to a conceptual geological model of the area.

Hydrogeological conditions

To obtain a more detailed picture on groundwater occurrence in the study area, geological and hydrological information must be translated into hydrogeological information and quantified in terms of hydraulic characteristics, groundwater flow regime and groundwater quality.

A basic division of geological formations, based on their hydraulic properties, includes the following:

- *Aquifers*: saturated zones in the subsurface, which are able to transmit relatively large fluxes of groundwater and which can produce enough accessible water to be of interest to humans (for example, coarse sand, sandstones, karstic limestones);

- *Aquitards*: saturated zones, which do not yield much water and permit only slow flow rates;

- *Aquicludes*: zones containing groundwater but having low permeability and extremely limited transmission of water;

- *Aquifuge*: contains no water and usually refers to completely impermeable zones (fresh hard rocks).

Many Internet sites provide comprehensive definitions of the above terms with examples (for example, http://or.water.usgs.gov/projs_dir/willgw/glossary.html).

Obviously, in water resources assessments, location of aquifers is an important goal. Nevertheless, information on less permeable and impermeable zones in the subsurface is also important in order to define the hydraulic status of aquifers (confined and unconfined) and to assess their vulnerability to pollution.

Within aquifers flow can be inter-granular, flow in fissures or a combination of the two. On hydrogeological maps using the official UNESCO legend, aquifers with inter-granular flow appear in blue colours while the fissured aquifers are shown in green colours. On these maps, brown colours refer to aquifers with local and limited groundwater resources. An updated guide and standard legend for hydrogeological maps was written by Struckmeier and Margat (1995), after a previous version published in 1970.

Climatological conditions

Intensity, frequency and duration of precipitation in combination with the rate of evaporation and land use are factors that can determine the recharge and quality of groundwater under the given hydrogeological conditions. Groundwater systems respond to temporal variations in climate. Because the response is relatively slow, they tend to reflect low frequency variations more than rapid climate changes. In arid regions, occurrence of groundwater might be related to wetter and cooler conditions in the past. Paleoclimate descriptions and data are therefore required in studies of non-renewable aquifer systems. Recharge estimations are further discussed in section 8.5.

8.2 REVIEW OF METHODS AND TECHNIQUES FOR GROUNDWATER RESOURCES AND MONITORING

In addition to the review of existing information, it is also useful to review existing methods and techniques used when collecting, processing and interpreting data for water resources assessment.

The International Groundwater Resources Assessment Centre (Jousma and Roelofsen, 2003) carried out an inventory of guidelines and protocols focusing on procedures, methods and techniques relevant to groundwater resources assessment and monitoring. The inventory is available at http://www.un-igrac.org/ (web page: guidelines and protocols) and includes the following methods:

- Drilling and well construction
- Surveys and field tests
- Field measurements and sampling
- Laboratory tests for soil quality and water quality
- Data analysis and mapping
- Monitoring networks
- Groundwater modelling and miscellaneous

It is important to be aware that some of the methods and techniques have not changed much over the last two decades (for example, drilling and well testing methods) whereas others are improving rapidly (for example, analysis methods, remote sensing, field equipment for monitoring, GIS software and groundwater modelling software). It is thus important to be aware of the developments of new methods and techniques that can save a lot of time or provide the analyst with new insights.

8.3 DELINEATION OF AQUIFERS

Delineation of aquifer geometry (lateral extent and depth) is an essential part of aquifer characterization. An aquifer may be formed by an alluvial strip along a river, single hard rock formation or complex of various hydraulically interconnected formations. Though the regional hydrogeological settings are usually known and approximate boundaries of aquifers are shown on hydrogeological maps, information on exact boundaries of transboundary aquifers is often lacking.

Lateral extent

In the absence of detailed hydrogeological maps, boundaries of individual aquifers can be deduced from geological information (for example, areal extent of formations) or from knowledge of the hydrological systems of the area (for example, water divides). Information from geological field surveys, hydrological information and information on patterns of existing wells can also help to estimate the lateral extent of an aquifer. Geological maps, aerial photographs and satellite images can be used to estimate lithological transitions. Topographic maps and remote-sensing products can be used to define surface water catchment boundaries.

The following considerations must be taken into account when using geological and topographical information:

– Conventional geological maps provide only limited information on vertical variations in lithology; they mainly depict what is at the surface;

– In tectonically complex areas (for example, folded structures), groundwater divides do not coincide with the surface water divides.

Results from monitoring groundwater levels and hydrochemical assessments may be used to identify boundary conditions of aquifers.

Thickness

Aquifer thickness and presence of interlayered aquitards are derived from the following:

– Borehole drilling data
– Geophysical well logs
– Surface geophysical studies

Borehole drilling data

Evaluation of cuttings and core descriptions can provide information on lithology and physical and chemical characteristics of subsurface formations. Variations in drilling rate also provide information relevant to hydraulic properties of the formations. In drillers' logs, reported "water struck-level" and "water rest-level" provide information on depth to groundwater and hydraulic status (confined or unconfined) of the aquifer.

A comprehensive summary of well drilling and design methods is presented in Kovalevsky et al. (2004). The IGRAC database (http://www.un-igrac.org/) shows 36 titles of guidelines and protocols for drilling and well construction.

Drilling data are usually representative only of the surroundings of a particular well. Extrapolation of drilling data to the inter-well areas depends on the well density in relation to the subsurface heterogeneity. General geological knowledge, in particular of the depositional environments, as well as specific knowledge of the area's stratigraphy, in combination with surface geophysics is used to estimate the thickness and continuity of aquifer layers.

Geophysical well logs

Logging is applied to determine the thickness, lithology and sequence of rock units in a vertical column. Interpretation of geophysical logs also provides insight into (some) physical aquifer parameters and groundwater salinity.

The most common logging methods used in groundwater studies include the following:

- Electrical methods (for example, spontaneous potential; resistivity and induction)
- Nuclear methods (for example, gamma log)

Sometimes a flow log is made to obtain an impression of relative permeability at different depths.

Table 8.1 shows lithological and salinity indications obtained from various methods in unconsolidated sediments.

The main value of borehole logging lies in correlation. Logs yield a continuous vertical picture of the subsurface and the similarity in response can be used to extrapolate information to the inter-well area.

Surface geophysical studies

Surface geophysical studies are used to map spatial distribution of geologic formations, to locate eventual faults and to obtain information on groundwater salinity. Common methods used in groundwater investigations include the following:

- Magnetic methods
- Electromagnetic methods
- Resistivity methods
- Seismic methods
- Gravity surveying

Table 8.1. Responses of various logs to lithology and salinity

Sediment type	*Pore fluid composition*	*Spontaneous potential*	*Resistivity*	*Induction*	*Gamma*	*Flow*
Coarse sand	Fresh	Positive	High	Low	Low	High
Coarse sand	Saline	Negative	Low	High	Low	High
Fine sand	Fresh	Positive	Medium	Medium	Medium	Medium
Fine sand	Saline	Negative	Extremely low	High	Medium	Medium
Clay	–	Negative	Low	High	Low	No
Peat	–	Negative	Low	High	Extremely low	Low

Source: Kovalevsky et al., 2004

The success of geophysical methods depends on distinct variations of physical properties of the Earth. Kovalevsky et al. (2004) give basic principles of geophysical methods used in groundwater studies.

Depth to groundwater

Depth to water struck (struck level) is often reported in drilling reports. This is the depth below the land surface where groundwater is encountered for the first time during drilling. Whether the ultimate depth to groundwater (rest level) is above or below struck level depends on the aquifer conditions (confined or unconfined). Wells with water level rising above the land surface are called artesian or "flowing wells".

Depth to groundwater represents the height of its hydrostatic pressure and as such it is subject to variations caused by natural and anthropogenic factors. Seasonal variations such as precipitation patterns and variations related to abstraction can only be evaluated if sufficient time series are available through long-term monitoring programmes.

Several measuring techniques are currently in use for groundwater level records. Basically these are divided into the following:

- Measuring systems using various tapes, floats, tubes and pressure transducers;
- Recording systems using analogous (paper) recorders, tele-transmission or data-loggers allowing measurements at variable time intervals.

8.4 ESTIMATION OF AQUIFER PARAMETERS

Description of aquifer parameters

Aquifer parameters have been defined for 3-D and for 2-D spatial schematizations.

The main physical properties of aquifer to be quantified are as follows:

- Porosity (P). Porosity is the ratio of void volume to the bulk volume (grains plus void space). Primary porosity refers to porosity developed during the formation of the rock. Secondary porosity refers to fractures, joints and solution cavities. Effective porosity is the volume of pores that is available for transport of water, divided by the bulk volume. Porosity is expressed as percentage.
- Hydraulic conductivity (K). The hydraulic conductivity is the ease through which water is able to move through interconnected pore space or fractures. The hydraulic conductivity depends both on the rock properties as well on water properties (fresh, saline). Hydraulic conductivity is expressed in metres/day.
- Transmissivity (T). Transmissivity is product of average hydraulic conductivity and saturated thickness of the aquifer. Transmissivity is expressed in m^2/day.
- Storativity (S). Storativity or storage coefficient is the volume of water released or stored in a column of the aquifer with a unit cross-sectional area (1 m^2) at a lowering or rise of head respectively of a unit distance (1 m). It applies to confined and semi-confined aquifers. Storativity is dimensionless.
- Specific yield (S_y) is the ratio of volume that a formation would yield by gravity to its own volume, under unconfined conditions. It represents very closely the effective porosity.

Table 8.2. Porosity and hydraulic conductivity ranges for some rock formations

Rock description	*Range of porosity (n) in percentage*	*Range of hydraulic conductivity (K) in m/d*
Gravel	0.2 – 0.4	10^2–10^3
Sand	0.2 – 0.5	1–10^2
Silt	0.3 – 0.5	10^{-1}–1
Clay	0.3 – 0.7	10^{-8}–10^{-2}
Fractured basalt	0.05 – 0.5	0–10^3
Karst limestone	0.05 – 0.5	10^{-2}–1
Limestone, dolomite	0.0 – 0.2	10^{-2}
Shale	0.0 – 0.2	10^{-7}
Fractured crystalline rocks	0.0 – 0.1	0–10^2
Dense crystalline rocks	0.0 – 00.5	$<10^{-5}$

Source: Fetter, 2000

For characterization of the vertical conductivity of aquitards (semi-confining layers):

- Hydraulic resistance (c) or leakage coefficient. This parameter characterizes the resistance of semi-pervious layers to leakage. It equals the thickness of the semi-confining layer divided by its vertical permeability. It is usually expressed in days.

- Leakage factor (L). For a simple system of an aquifer with transmissivity T covered by a semi-confined layer with hydraulic resistance c, the leakage factor equals $L = (T.c)^{0.5}$. The parameter expresses the hydraulic contrast between the aquifer and the semi-confining layer; large values of L indicate a large hydraulic contrast.

Detailed descriptions of aquifer parameters with relevant units can be found in hydrogeological handbooks, for example, Fetter (2000).

Table 8.2 gives porosity and hydraulic conductivity ranges for some rock formations.

Methods of estimation of aquifer parameters

Generally, three methods may be distinguished to estimate aquifer parameters, as follows:

- Laboratory tests of samples from geological formations composing the aquifer
- In situ pumping tests, single-well tests and flow tests
- Flow net analysis or inverse modelling beyond the local level

Laboratory tests

A laboratory test may yield information on the hydraulic conductivity (K) and the porosity. The test includes determining the granular composition of unconsolidated sediments or permeameter tests on consolidated rocks. The tests may give an indication of the parameters of the rocks composing the aquifer, but they will not provide accurate estimates of the parameters outside the sampling point.

In situ pumping tests and single-well tests

The most reliable and commonly used method for estimating aquifer parameters is based on generating an artificial, temporary flow pattern, by means of pumping and measuring water levels during a certain period. These methods are referred to as follows:

- Pumping test, where the water is pumped from a well and the drawdown is measured in the well and in piezometers at known distance(s) from the well. The aquifer parameters obtained during such pumping tests include transmissivity (T), storage coefficient (S) and leakage factor (L).

- Single-well test, where the water is pumped and the water level is measured only in the well; then only measurements of transmissivity (T) can be obtained.

The principles of pumping tests and instructions on how to conduct a pumping test under different conditions are discussed in detail by Kovalevsky et al. (2004).

Normally pumping tests are carried out in representative pumping wells and piezometers soon after completion of construction. It is advisable to carry out the pumping tests in piezometers, which are representative of wider areas, and which are not very close to roads with heavy traffic or railway lines. Furthermore, the pumping well or piezometer should be in a location where the pumped water can be safely discharged.

A comprehensive overview of the main methods used for analysis and evaluation of pumping data is given by Kruseman et al. (1991). Special attention is given to evaluation of hydraulic characteristics in fractured rocks since conventional well flow equations do not adequately describe the flow in such reservoirs.

Manual calculation has been traditionally performed for the calculation of aquifer parameters, with a best-fit match to a hand-drawn plot. Today, commercial software supports the analysis of pumping tests, slug tests and step tests, using both traditional manual techniques and numerical optimization. They offer the utility to import data from just about any source using a sophisticated data import wizard. They also permit creation of a database giving details of time, drawdown, pumping rates, distance and dimension of the wells. The different programs generally provide a similar approach with respect to data entry; however, major variations are seen in the type of analysis and reporting.

Commercial software packages for such analyses can easily be obtained by an Internet search for “pumping test software”.

Flowing well tests and slug tests

Alternative field methods for determining the hydraulic characteristics include the following:

- Flowing well test performed in artesian wells. This method is based on the difference between the static piezometric head after shutdown and the outflow opening of the well;

- Slug test using a small volume of water removed suddenly from a well. Alternatively, water is added to a well.

Technical aspects of these methods and analyses of data are discussed in Kovalevsky et al. (2004) and Kruseman et al. (1991).

8.5 GROUNDWATER RECHARGE ESTIMATION

Groundwater recharge and methods for estimation

Groundwater recharge is produced either by direct infiltration of precipitation (direct recharge) or by the infiltration of water from surface water systems (indirect recharge). Artificial recharge is a special form of indirect recharge produced by human interference. A special case is formed by non-renewable aquifers. Non-renewable aquifers are groundwater bodies that do not receive significant present-day recharge.

It is important to distinguish between the infiltration (potential recharge) that is available at the ground surface and the actual recharge that reaches the body of underground water. The actual recharge may be less than the potential because of factors such as evapotranspiration from the unsaturated zone, the presence of poorly permeable zones between the ground surface and the permanent water table, or the inability of the aquifer to accept all the potential recharge (Kovalevsky et al., 2004).

The main factors which determine the volume of water that can recharge the aquifer system are as follows:

- Volume and intensity of precipitation
- Runoff
- Evapotranspiration
- Presence of surface water bodies
- Topography of land surface
- Infiltration capacity of soil
- Permeability of subsoil domain
- Vertical hydraulic gradient
- Artificial and induced recharge

The first stage of groundwater recharge estimation should involve collecting existing data on climate, hydrology, geomorphology, geology and land use. Evaluation of these data can yield a conceptual model of recharge and can provide a first insight into the likely mechanism and potential volume. Methods of estimating recharge are discussed in Lerner et al. (1990) and more recently in Scanlon et al. (2002) and Beekman and Xu (2003).

Techniques for estimating groundwater recharge are subdivided into various types, on the basis of the three hydrologic domains from which the data are obtained:

- Surface water domain
- Unsaturated domain
- Saturated domain

Within each zone, techniques can be subdivided, according to the approach used, into the following:

- Physical approach. These techniques rely on direct measurements of hydrological parameters or on estimates of soil and/or aquifer physical parameters.

- Tracer approach. In these techniques, a natural or artificially applied tracer is used to follow water movement in both the unsaturated and saturated zones.

- Numerical modelling approach. Numerical modelling methods take transient flows and storage changes into account and can include spatial variability of physical parameters. Models based on known values of hydraulic head are referred to as inverse models.

The objective of the recharge study should be known prior to selection of the appropriate method for quantifying groundwater recharge, as this may dictate the required space- and timescales of the recharge estimates (Scanlon et al., 2002). A water resources assessment requires information on recharge at large spatial and temporal scales (Beekman and Xu, 2003).

Many techniques are based on the water-budget equation, which states that the difference between inflows and outflows equals change in storage. A summary of the water budget approach is given by Scanlon et al. (2002). Methods for measuring or estimating various components of the water budget are described in Hillel (1980), Rosenberg et al. (1983) and Tindall and Kunkel (1999).

The common recharge estimation methods are summarized in Table 8.3 (based on Scanlon et al., 2002 and Beekman and Xu, 2003).

Table 8.3. Common recharge estimation methods

Approach/method	*Principle*	*Data required*	*References*
Physical approach			
Channel-water budget	Recharge derived from difference in flow upstream and downstream accounting for evapotranspiration (ET), in- and outflow and channel storage change	Stream-gauging data	Lerner et al., 1990; Lerner, 1997; Rushton, 1997
Seepage meters	Point estimates of water fluxes using cylinders with attached reservoir of water	Infiltration rates measurements on daily or weekly basis	Kraatz, 1977; Lee and Cherry, 1978; Taniguchi and Fukuo, 1993
Hydrograph separation/base-flow discharge	Stream hydrograph separation based on water-budget approach	Base-flow outflow, ET, abstraction, bank storage estimates	Halford and Mayer, 2000; Arnold et al., 1995; Xu et al., 2002
Lysimeters	Drainage proportional to moisture flux measured in containers filled with soil with or without vegetation	Precipitation, water storage, evapotranspiration	Allen et al., 1991; Young et al., 1996; Bredenkamp et al., 1995
Zero flux plane	Soil moisture storage changes below zero vertical hydraulic gradient proportional to moisture flux	Soil matrix-potential measurements; soil–water-content measurements	Richards et al., 1956; Healy et al.,1989; Gieske, 1992
Darcy law	Subsurface water flux is calculated by multiplying the hydraulic conductivity by the hydraulic gradient	Hydraulic gradient; hydraulic conductivity	Theis, 1937; Belan and Matlock, 1973; Stephens and Knowlton, 1986
Water table fluctuation	Water level response proportional to recharge in unconfined aquifers	Specific yield, water-table height, precipitation data	Hall and Risser, 1993; Bredenkamp et al., 1995; Healy and Cook, 2002
Tracers			
Heat tracer	Temperature monitoring in ephemeral streams to estimate infiltration from surface bodies	Diurnal temperature of surface water at various depths	Stallman, 1964; Lapham 1989; Ronan et al., 1998
Isotopic tracer	Difference is stable-isotope signature of rivers and local precipitation (qualitative information)	Stable isotopes of oxygen and hydrogen	Taylor et al., 1989, 1992; Stuyfzand, 1989
Applied tracers (unsaturated zone)	Chemical (bromide, organic day) or isotopic traces (tritium) are applied as pulse at the soil surface	Measurements of applied tracer at various depths of soil profile	Aeby, 1998; Forrer et al., 1999; Scanlon and Goldsmith, 1997
Historical tracers/ groundwater dating	Vertical distribution of tracer as a result of activities in the past (thermonuclear tracers, contaminants)	Concentrations of tracers; sources location, possible chemical reactions	Phillips et al., 1988; Scanlon, 1992; Cook and Solomon, 1997
Environmental traces/chloride mass balance	Profiling: Drainage is inversely related to Cl concentration in the unsaturated-zone pore water or groundwater	Chloride concentrations at various depths	Eriksson and Khunakasem, 1969; Scanlon, 2000; Phillips, 1994
Numerical modelling			
Watershed modelling	Numerical precipitation-runoff modelling; recharge estimated as a residual term	Components of the water budget	Singh, 1995; Kite, 1995; Sami and Hughes, 1996
Unsaturated-zone modelling	Unsaturated flow simulation, for example, by using bucket model or numerical solutions to Richards equation	Soil moisture data, boundary conditions	Flint et al., 2002; Bredenkamp et al., 1995; Lerner et al., 1990
Groundwater modelling	Indirect groundwater modelling	Hydraulic conductivity; groundwater ages boundary conditions	Sanford, 2002; Portniaguine and Solomon, 1998; Bredenkamp et al., 1995

Source: from Scanlon et al., 2002 and Beekman and Xu, 2003

An example of the comparison of the different approaches and recharge methodologies showing a large range of results, depending upon approach, initial estimates of recharge rate and scale, is provided in Scanlon et al. (2002).

At a regional scale, estimations based on monthly data are probably adequate to estimate the recharge, provided this is undertaken on an aquifer specific basis. The greater variability in space and time in arid and semi-arid areas needs to be taken into account. As the study area decreases and/or the required level of accuracy and precision increases, daily precipitation and flow data related to particular recharge events, obtained within well-defined boundary conditions, become more critical.

Some of the common methods are as follows.

Water-table fluctuation method

The water table fluctuation method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table (Healy and Cook, 2002). Recharge is calculated as:

$$R = S_y \, dh / dt = S_y \, \Delta h / \Delta t \qquad (8.1)$$

where S_y = specific yield; h = water-table height; and t = time.

The method is best applied in regions with shallow water tables with a large rise of the water table over a short period. The method can be applied in both humid and arid regions. The main limitations are related to the identification of the cause of water-level fluctuations (influence of air pressure and abstraction) and estimating specific yield.

Chloride mass balance

The method is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface (Beekman and Xu, 2003). Total recharge can be calculated, using a simplified mass balance requiring certain assumptions.

The method for the saturated zone may be especially useful in areas where groundwater levels do not fluctuate or data on groundwater levels are lacking. The main limitations are related to overestimation due to preferential flow in the unsaturated zone and to influence of dissolution of evaporites and mixing of saline water. Anthropogenic sources of chloride (such as fertilizers), if present, may affect the accuracy, and data on land use are helpful in this regard. Long-term rain-quality data are needed for application of this site-specific method.

Tracer techniques

Chemical or isotopic tracers are applied as a pulse at the soil surface or at some depth within the soil profile (Scanlon et al., 2002). The recharge rate is calculated as:

$$R = \frac{\Delta z}{\Delta t} \theta \qquad (8.2)$$

where Δz = depth of the tracer peak; Δt = time between tracer application and sampling; and θ = volumetric water content.

The maximum water flux that can be measured depends on the depth to the water table.

Historical tracers (for example, tritium/helium and chlorofluorocarbons) are used for dating groundwater. By dating water at several points in a vertical profile, groundwater velocity and subsequently the rate of recharge can be estimated.

Table 8.4. Recharge factors

Mean annual precipitation (MAP) range		*Mean annual infiltration*
Minimum	*Maximum*	*Per cent of MAP*
0	300	3
300	600	6
600	900	9
900	1 200	12
1 200	1 500	15
1 500	1 800	18
1 800	2 100	21

Source: DWAF, 2003

Accuracy of tracer techniques with regards to the recharge estimate is rather low. The methods are usually costly and are sensitive to environmental conditions.

Practical approaches for (preliminary) recharge estimation

Recharge from precipitation

In South Africa (DWAF, 2003), a method for preliminary recharge estimation was introduced that takes mean annual precipitation per catchment into account. The precipitation-recharge ratios used are given in Table 8.4. Such estimates vary depending on the climatic zone and hydrogeological conditions, and care has to be taken in transferring results elsewhere.

Since rock types differ in their infiltration capacity, this method can be combined with an aquifer specific factor, varying between 0.5 for low permeability aquifers and 1.5 for primary aquifers.

Recharge from rivers

A practical approach for arid regions is described in Van der Gun and Azis (1995). It is applicable for cases where runoff from a mountainous river catchment forms the predominant source of recharge for a “downflow” located unconfined aquifer system.

A reasonable estimate of recharge can be made by identifying the catchments that drain towards the aquifer unit considered, estimating their mean annual yield (runoff), and allocating this yield in defined proportions to groundwater recharge, “net” water consumption in surface irrigation areas and surface water outflow. The proportions depend on local conditions. If the flow in the streams disappears completely, without being diverted for surface water irrigation, then it may be assumed that some 95 per cent of the flow will be converted to recharge. If the flow disappears but not without part of the flow being diverted for spate irrigation, then the groundwater recharge can be estimated as the undiverted part of the flow plus irrigation water lost to the subsurface, which in the case of spate irrigation equals at least half of the diverted flow.

8.6 GROUNDWATER HYDROCHEMISTRY

The natural chemical composition of groundwater is highly variable. It is controlled by many physical, chemical and biological processes and depends on the quality of infiltrating water, climatic and topographical conditions, mineralogical composition of soil and rock environment, and interactions between the soil, rock, gas and water system. The rock environment in which groundwater moves, aquifer thickness and permeability, length of groundwater pathways, groundwater residence and surface contact time within a given aquifer and amount of recharge have decisive influence on the chemical composition of groundwater. Generally, groundwater in recharge areas and shallow aquifers where contact times are of the order of years or decades is lower in total dissolved solids than groundwater in transit and discharge areas and deeper aquifers where residence time may be centuries and flow velocities very low.

Anthropogenic influences determine the final groundwater quality and suitability for various purposes. Based on the total contents of dissolved solids, the following division is made:

- Fresh groundwater (<1 000 to 2 000 mg/l)
- Brackish groundwater (2 000 to 20 000 mg/l)
- Saline groundwater (20 000 to 50 000 mg/l)
- Brine (>50 000 mg/l)

Detailed maps showing groundwater quality are sometimes available, but mostly only saline water zones are shown on hydrogeological maps.

The natural quality of groundwater in many aquifers of the world is suitable for drinking purposes and other uses. However, some groundwater contains various elements, dissolved from the weathered rock matrix and ore deposits, which limit its fitness for use or increase its treatment requirement.

In sedimentary rocks, particularly sandstones, calcium carbonate is often the dominant cementing material which dissolves in groundwater though silica and ferrous compounds are also common. In carbonate rocks, limestone and dolomite, the solution processes are highly dependent on temperature and the presence of carbon dioxide which affects the acidity of the water, but calcium and magnesium salts predominate. Groundwater in sulphate-bearing sediments such as gypsum is often brackish as is groundwater from salt-bearing rocks.

Igneous rocks are often of low permeability though locally important aquifers can be found in areas of extrusive rocks (lava, volcanic ash, tuff and breccia). Silica content of groundwater is highest where there are high sodium levels and elevated temperatures and lowest where there are high levels of ferromagnesium minerals.

Metamorphic rocks are of generally low permeability and solubility so dissolved solids in any groundwater are low.

Groundwater rich in sodium is not suitable for consumption by children or vulnerable adults and, when used for irrigation, alters the physical properties of the soil and affects the growth of agricultural products. High concentrations of chloride have long-term effects on kidneys and intestines and water containing more than 350 mg/l is not suitable for irrigation and industrial processes. Sulphate in drinking water affects the gastrointestinal tract and nitrate-rich water has a potential toxic effect on infants.

Shallow water aquifers, particularly those in gravel and sandy sediments, are vulnerable to pollution from a variety of surface sources. The inappropriate discharge of untreated human or animal waste into permeable ground can produce groundwater with high levels of bacteria and can promote the spread of pathogens. Excessive use of fertilizers and pesticides can leave significant amounts of these chemicals and toxic substances in the infiltration water and make the aquifer unusable for drinking water and other uses. It is therefore important that both point-specific and diffuse sources of pollution are considered in relation to abstraction points and treatment requirements.

8.7 LONG-TERM RESOURCE AVAILABILITY

Groundwater reservoirs play an important role in water resources; the volumes of storage available can be vast and they need to be considered in the same way as surface reservoirs when considering the limits of sustainable abstraction even though long-term reserves and indicators of depletion may be much less obvious than for surface storage. Key to sustainable exploitation of any aquifer is a full understanding of its recharge, storage and through-flow characteristics and how these vary on a seasonal and multi-annual basis.

The effective available storage in an aquifer will be determined by the range of levels that can be accommodated in extraction boreholes. Actual volumes of available storage at any time need to be estimated through assessment of aquifer extent and effective porosity.

Through-flow can be assessed by considering hydraulic gradients across an aquifer from borehole records and assessments of the macro-scale hydraulic conductivity of the rock formations concerned.

Long-term simulations can be constructed from these assessments using long-term series of recharge and outflow to assess how the underground storage available can be used most effectively to deliver water resources without causing long-term depletion of the aquifer.

Some major aquifers are effectively geological relics and do not have any obvious contemporary source of recharge. These include the Nubian sandstone aquifer in North Africa, which plays a major role in providing essential water for Libya, Egypt, Chad and Sudan, but this water is several thousand years old and there are no significant sources of recharge under current climatic conditions. Exploitation of such resources is more akin to extraction of oil or other long-term mineral reserves than the inter-seasonal or interannual use of groundwater storage in surface-connected aquifers (Foster and Loucks, 2006). The States concerned have formed a joint authority to address issues relating to the exploitation of the aquifer and there is ongoing work to better understand the aquifer and the impacts of its use.

CHAPTER 9. WATER AVAILABILITY

Assessment of total water availability requires an assessment of water balance and projection of this into the future (Australian Bureau of Meteorology, 2010). To assess water balance, a conceptual catchment framework as shown in Figure 9.1 can be used. This shows similar stores and fluxes to the diagram in Figure 2.1, but to aid evaluation of flows an additional storage is added for the water supply system.

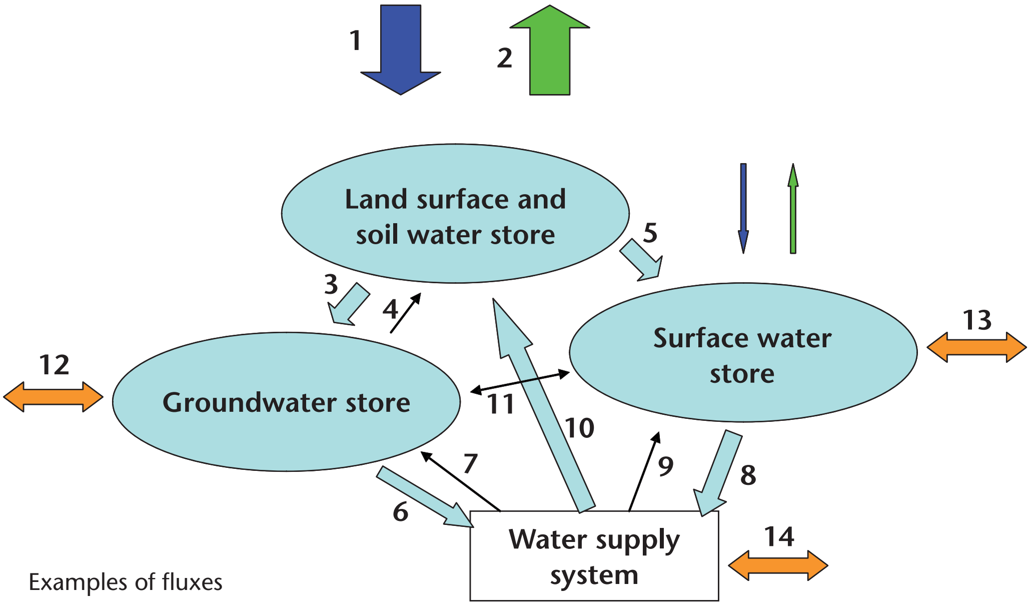
The four water stores are briefly described as follows:

- ***Land surface and soil water store***: primarily water in surface soil layers, wetlands, bogs and shallow surface depressions;
- ***Surface water store***: water in rivers, lakes, canals, dams and storage reservoirs;
- ***Groundwater store***: water in underground storage though typically only the volumes above some datum considered as the lowest practical variation or limit of extraction are considered;
- ***Water supply system***: water in service reservoirs, tanks, pipes and treatment works.

The volume in the water supply system is generally treated as constant and does not need to be evaluated with any great accuracy, but the flows to and from this storage are a crucial part of the overall assessment.

For each store and for any time interval t_0 to t_1 the water balance depends on the mass balance equation:

$$\text{Storage at time } t_1 = \text{storage at time } t_0 + \text{net inflow in time interval } t_1 – t_0$$



Examples of fluxes

1. Precipitation
2. Evapotranspiration
3. Groundwater recharge
4. Capillary rise
5. Runoff, stormwater
6. GW extraction
7. Leakage, aquifer injection
8. Surface water diversion
9. Return flows
10. Irrigation
11. Groundwater/surface water interaction
12. Groundwater flow in/out of catchment
13. Surface water flow in/out of catchment
14. Wastewater, interbasin flow

Figure 9.1. Conceptual diagram of sub-catchment water balance framework

9.1 CLASSIFICATION OF WATER RESOURCES

When considering water use, three classifications can be considered, as follows:

- ***Green water***: water that is used where the rain falls, or what supplies terrestrial ecosystems and rain-fed crops from the soil moisture zone, and it is green water that evaporates from plants and water surfaces into the atmosphere as water vapour;

- ***Blue water***: water that is directly associated with aquatic ecosystems and flow in rivers, lakes or groundwater;

- ***Grey water***: water required to dilute polluted return flows.

The concept of blue and green water was developed by Falkenmark and Rockström (2004).

A further major consideration is the minimum flows required in the natural system to maintain acceptable environmental conditions and maintain natural habitats.

In general, green water use will involve relatively small volumes of local storage that will have little impact on the overall catchment though many uses such as irrigation or small-scale horticulture will be consumptive uses. Water availability is clearly limited by the net precipitation available at the given site less any requirement to provide downstream flow.

Blue water is the main consideration in water resources assessments and indicator of water availability. It will include both consumptive and non-consumptive uses for human, industry and agricultural purposes. The limits of extraction depend on the overall assessment of available resources as discussed in section 9.2 below.

The flows of grey water required will depend on the level of dispersed pollutants used in the catchment, the environmental standards required in the relevant water bodies and the quality of treatment of effluent flows.

9.2 NET AVAILABLE RESOURCES

Once the main factors influencing all the primary processes and fluxes in the water balance are understood and quantified, this understanding can be used to assess the long-term availability of net resources. Generally, this will require long-term simulation modelling which includes a range of climate change and development scenarios. Climate change impacts are discussed in section 10.4. Simulation models may be relatively simple or exceedingly complex, but it is important that they are capable of reflecting the key changes that are likely to be expected and particularly any non-linear responses in the hydrological system.

From this simulation modelling, which might well encompass 1 000 years of synthetic data for each range of climate and catchment conditions, it should be possible to construct statistics for critical flows, drought periods and other extremes from which the reliability of different abstraction regimes can be assessed. Clearly it is important that input data streams used for the simulations, such as meteorology, incorporate realistic extremes for the relevant climate region, even if these have not been experienced in the particular location in the recent historical record.

Different water uses clearly require different levels of reliability and where demand management can be used at times of shortage this should be taken into account in setting reliability levels. This is an issue for water resources management which is outside the scope of this publication.

9.3 EXPLOITABLE WATER

Not all natural freshwater, surface water or groundwater is accessible for use. Exploitable water (manageable water resources or water development potential) consider factors such as the economic and environmental feasibility of storing floodwater behind dams or extracting groundwater; the physical possibility of catching water which naturally flows out to the sea; and the minimum flow requirements for navigation, environmental services and aquatic life.

This concept varies according to the following:

- Natural conditions that may affect the development of water resources (regularity of the water regime, fragmentation of the hydrographic or hydrogeological systems, convenience of sites for dams and water quality);

- The importance of demand for water, which will determine the acceptability of internal and external costs of water development and management; it also involves arbitration for allocation between in situ use (reservation) and ex situ use or abstraction;

- Geopolitical constraints such as agreements to minimum transboundary flows.

As it depends on the choice of a set of criteria (physical, socio-economic, environmental, and so forth), this concept varies from country to country. It can also evolve according to demand pressures. However, it represents a realistic vision of the renewable resources available for use in a given situation and period.

In general, exploitable resources are significantly smaller than the natural resources (FAO, 2003).

9.4. POSSIBLE ADDITIONAL SOURCES OF WATER SOURCES

This section aims to discuss some of the means by which water resources use beyond exploitation of surface or natural groundwater sources can be achieved so that a basin's total "water resources" can become greater than the natural net precipitation as reflected in river flows and groundwater recharge and the storage available in wetlands, lakes and reservoirs. In most cases detailed considerations for implementation will be an aspect of water resources management that is beyond the scope of this publication, but their potential may well be taken into account in water resources assessments.

Managed groundwater recharge (formerly referred to as "artificial recharge")

This covers a range of techniques for enhancing the natural rate of groundwater recharge using surplus water available in the surface environment. Examples include the temporary impoundment of floodwater in permeable areas and the injection of surface flow or partially treated effluent water directly into aquifers through boreholes. By increasing the rate of recharge of aquifers, this increases the effective storage that can be utilized. In water resources assessment the availability of such measures may reduce the volumes that need to be assumed as lost in flood outflows and effluent discharge.

Precipitation harvesting

The capture of precipitation at source for local use is generally referred to as rainwater harvesting.

In agricultural and horticultural systems the storage of excess precipitation running off land and buildings, including greenhouses, can make a significant contribution to irrigation needs if sufficient storage can be provided.

In the urban environment most precipitation harvesting systems that capture precipitation from roofs and paved areas are small scale, although in some areas they provide an essential element of household supply where reliable mains water is not available. Peters (2006) provides an assessment of the costs of providing water supplies through rainwater harvesting for an island community that compare very favourably with the alternative in this case, which was desalination.

Desalination

In general desalination will be a last resort in the provision of water resources; however, this has become an important source of water in countries and regions where the significant energy costs can be afforded. Through processes such as reverse osmosis that use high pressures to pass water through a semi-permeable membrane, almost any source of water from brackish groundwater or the sea can be converted into water suitable for human consumption. The energy required will depend on the salinity of the water source. It is therefore the availability of energy and financial investment for the construction of desalination plants rather than the availability of water that determines the availability of supply. Clearly, any such reliance on energy use raises questions of long-term sustainability unless reliable supplies of renewable energy can be harnessed.

Recycling and re-use

This covers a wide range of water management techniques. In many European countries, water returned to rivers from domestic or industrial use is re-abstracted for similar uses further downstream and in the larger catchments this may occur over several cycles between the source and the sea. This is carried out on a large scale but depends on high standards of effluent treatment and on good quality control in the treatment of water for subsequent use.

At a more local level many industrial processes have been modified to make more effective use of water through treatment and recycling. Many cleaning processes can make use of the same water through several cycles with appropriate screening and treatment.

In many cases, agriculture can make use of water discharged from urban areas and industrial plants where quality is appropriate. Cereals, fodder crops, oil seeds and biofuels are all potentially low-risk products that can tolerate quite high levels of nutrients. Indeed, many urban areas should be considered as useful sources of water and nutrients for agriculture rather than sinks for water resources.

CHAPTER 10. IMPACTS ON WATER RESOURCES

This chapter sets out some of the long-term impacts that need to be taken into account in any assessment of sustainable water availability and incorporated explicitly in any long-term simulation modelling. In understanding these impacts, it is important to understand what is meant by consumptive use. Consumptive use is the difference between the total quantity of water withdrawn from a source for any use and the quantity of water returned to the source, for example, the release of water into the atmosphere; the consumption of water by humans, animals and plants; and the incorporation of water into the products of industrial or food processing.

10.1 ABSTRACTIONS

Abstractions from the water resources system cover all areas of water use whether sourced from surface or groundwater systems. The major areas of use are covered below.

Crop water demand refers to the amount of moisture a crop would use given an unlimited supply of water. The crop water need (evapotranspiration crop) (FAO, 1986) is defined as the depth (or amount) of water needed to meet the water loss through evapotranspiration. In other words, it is the amount of water needed by the various crops to grow optimally.

The crop water need always refers to a crop grown under optimal conditions, that is, a uniform crop, actively growing, completely shading the ground, free of diseases, and favourable soil conditions (including fertility and water). The crop thus reaches its full production potential under the given environment.

The crop water need mainly depends on the following:

- The climate: in a sunny and hot climate crops need more water per day than in a cloudy and cool climate;
- The crop type: crops such as maize or sugarcane need more water than crops such as millet or sorghum;
- The growth stage of the crop: fully grown crops need more water than crops that have just been planted.

Another approach to the description of water demand is the water footprint. This sums the volume of water required throughout the production, processing and consumption per unit of output. Table 10.1 shows typical water footprints of a range of staple products.

Clearly, trade in many agricultural products involves virtual export/import of significant quantities of water, and import of food products from non-water stressed areas is one approach to dealing with countries that lack adequate water resources. On a regional and international scale, any significant changes in patterns of consumption between vegetarian and meat-based diets have major implications for future water consumption.

Public water supply

Public water supplies cover all those abstractions used to supply multiple users including households, commerce and industry through a common abstraction treatment and distribution system. In general, increased affluence in society tends to increase per capita domestic water usage, because more water-using appliances are installed, more water is used for personal washing and so forth, and at the highest levels significant amounts of water are used for garden watering, swimming pools and other amenity uses. See Table 10.2 for some examples of annual domestic

Table 10.1. Some typical water footprints

Product	*Unit of output*	*Water footprint (litres)*
Beef	kg	15 500
Poultry	kg	3 900
Rice	kg	3 400
Wheat	kg	1 300
Maize	kg	900
Millet	kg	5 000
Milk	Litre	1 000
Beer	Litre	300
Paper from wood pulp	Ream A4 (500 sheets)	5 000
Cotton (final textile)	kg	11 000

Source: www.waterfootprint.org, Hoekstra and Chapagain, 2008

use per capita in different societies. Clearly, in those countries with lowest use, consumption is significantly constrained by the lack of access to effective piped water distribution systems.

However, in more affluent societies there are also opportunities to limit water use, such as through encouraging use of more water-efficient appliances, and universal metering of domestic supplies can reduce consumption. In Western Europe, the water consumption levels have stabilized or are even decreasing. At times of water stress it may be possible to reduce demand by banning many non-essential uses, including car washing, garden watering and other amenity activities. Clearly, the ability to operate such management measures depends on the degree of control that can be exerted by the water provider and the degree of cooperation that can be achieved from users.

A further consideration is the quality of treatment of effluents from public systems. As treatment improves then the amount of dilution water required to maintain satisfactory environmental conditions downstream is reduced and opportunities for re-use are increased.

Table 10.2. Average annual per capita domestic water use in selected countries

Country	*Average domestic water use m^3/capita/year*
Australia	341
Canada, Armenia	279
United States of America	217
Japan	136
France, Spain	105
Russian Federation	98
Brazil, Suriname	70
South Africa, Peru, Iraq, Republic of Moldova	57
India, United Kingdom	38
Morocco, Guyana, Zambia, Indonesia, Netherlands	28
Paraguay, Kenya, Togo	15
Chad, Rwanda, Sierra Leone	5
Somalia, Ethiopia	2

Source: extracted from Hoekstra and Chapagain (2008) and the International Water Association (http://www.waterfootprint.org/?page=files/home)

Table 10.3. Water footprint of industrial products by output value (in United States dollars)

Country	*Water footprint (litres) per US$*
United States of America	100
Germany, Netherlands	50
Canada, Australia	10–15
China, India	20–25

Source: www.waterfootprint.org, from Hoekstra and Chapagain (2008)

Irrigation

Water use for irrigation depends on the area irrigated, crops cultivated, cropping patterns, climatic conditions and the type of irrigation system used. Likely extensions to irrigated areas may need to be assessed by considering climate changes and production pressures that could lead to increased demand. Future changes in crops or cropping patterns are difficult to predict but should be considered in forward water resources projections. Changes in climate that could change patterns of precipitation or evapotranspiration should be a key consideration in water resources assessments. However, where water is likely to become scarcer or more expensive, more effective irrigation systems may be adopted. For example, wasteful flood irrigation may well be replaced by more selective water applications and spray irrigation reduced in favour of trickle irrigation systems. Ultimately in areas of high water stress, highly controlled hydroponic systems may be adopted to minimize water use per unit of output.

Industrial use

Industrial use depends on the nature and scale of industry in an area. Future demand estimates should take account of industrial development policies of the State and the potential for future exploitation of natural resources or development of employment opportunities.

It is difficult to measure the water footprint of specific products because of the complexity and diversity of industrial processes. However, Table 10.3 shows averages for industrial products from a range of countries.

10.2 LAND USE CHANGE

Land use affects the actual rate of evaporation, characteristics of surface runoff and rates of infiltration, all fundamental factors that need to be considered in water resources predictions.

Agriculture

It is estimated that some 70–80 per cent of global water usage is for agriculture. Different crops and types of agriculture will have different evapotranspiration rates and therefore different levels of water demand. Some examples of the water requirements of different crops are given in Table 10.4.

Intensive stock rearing will require a greater supply of water than extensive grazing, and water demand will generally increase in conversion from grassland to arable. Also, different methods of cultivation will affect the rate of runoff and infiltration.

The widespread use of fertilizers and pesticides affects the quality of surface runoff from agricultural areas and the quality of groundwater. Excess nutrients or toxins mean that water

Table 10.4. Variations in water requirements of different crops from tests in the Missouri and Arkansas River basins

Crop	*Water requirement (mm/yr)*	*Crop*	*Water requirement (mm/yr)*
Forage including alfalfa	590–800	Apples	640–795
Barley	405–555	Peas	415–590
Wheat	415–550	Potatoes	420–520
Millet	245–285	Sugar beet	490–765
Maize	335–520	Sunflowers	365–425
Sorghum	325–450		

Source: extracted from Wilson, 1985

downstream may become unusable for most purposes or only suitable for use after very expensive treatment processes.

Deforestation

Rates of interception and evapotranspiration in forests are generally high so deforestation generally leads to an increase in surface runoff. Also, the additional soil erosion from deforested areas can often lead to rapid siltation of storage reservoirs, reducing the effective storage capacity.

Urbanization

Urbanization creates extensive areas of hard surfacing in the form of roofs, roads and other paved areas. These lead to rapid runoff of storm precipitation and very significant reductions in infiltration to groundwater. Urban areas are also major sources of pollution from human waste, industry, cleaning fluids and food processing. Transport systems also produce pollution from spilt petrochemicals, rubber compounds and, in cold climates, salt used for de-icing.

10.3 POLLUTION

Whilst sources of pollution do not directly affect the quantity of water in a catchment, they do have a large impact on the effective amounts of useable water that is available and the environmental quality of water bodies. Cumulatively, all sources of pollution can have a significant impact on effective net resource availability.

When considering pollution management, a distinction is often drawn between dispersed and point sources because approaches to management and control are different.

As noted above, agriculture can be a major source of dispersed pollution, particularly from intensive arable or livestock production. Urban areas and road networks also produce a range of pollutants. In addition, there are point sources of pollution in many catchments, generally associated with particular discharges from industrial plants, waste disposal sites or sewage treatment facilities.

Even relative small sources of pollution can render whole water bodies unusable without expensive treatment and can cause widespread environmental damage. Excess nutrients result in eutrophication and can lead to extensive toxic algal blooms.

10.4 CLIMATE CHANGE

Climate change will generally be a significant element in forward projection of water availability. Normally a range of climate scenarios will be considered to assess the sensitivity of estimates and policy options.

Climatic projections based on global climate models

The Intergovernmental Panel on Climate Change (IPCC), in its Fourth Assessment Report (Chapter 10, Working Group I (WG I), IPCC (2007*a*)) presented the wide range of climatic projections based on climate models of different complexity forced with concentrations of greenhouse gases (GHGs) and other constituents derived from various emission scenarios. Emission scenarios are based on different assumptions about the future economic development and world population dynamics leading to essentially different growth in atmospheric concentrations of major GHGs (Nakicenovic and Swart, 2000). Projected climate change is thus scenario-dependent so that the actual changes in temperature and precipitation will be significantly affected by the actual emissions that occur.

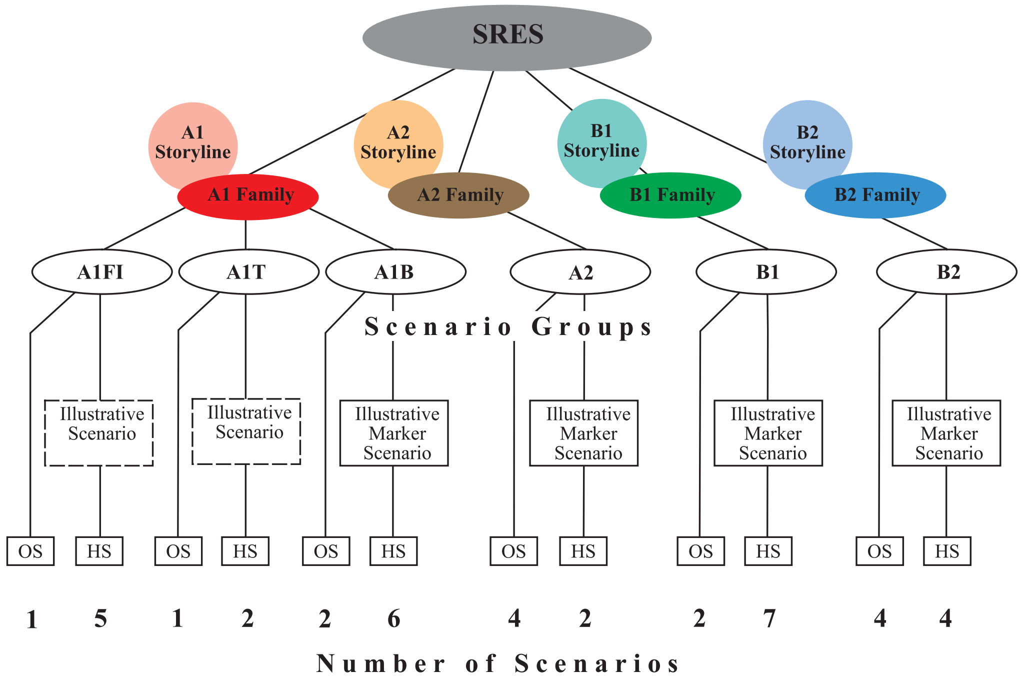
Four qualitative storylines yield four sets of scenarios called “families”: A1, A2, B1 and B2. Altogether 40 Special Report on Emissions Scenarios (SRESs) have been developed by six modelling teams. All are considered equally valid with no assigned probabilities of occurrence. The set of scenarios consists of six scenario groups drawn from the four families: one group each in A2, B1, B2, and three groups within the A1 family, characterizing alternative developments of energy technologies: A1FI (fossil fuel intensive), A1B (balanced) and A1T (predominantly non-fossil fuel). Within each family and group of scenarios, some share “harmonized” assumptions on global population, gross world product and final energy. These are marked as “HS” for harmonized scenarios; “OS” denotes scenarios that explore uncertainties in driving forces beyond those of the harmonized scenarios. The number of scenarios developed within each category is shown. For each of the six scenario groups an illustrative scenario (which is always harmonized) is provided. Four illustrative marker scenarios, one for each scenario family, were used in draft form in the 1998 SRES open process and are included in revised form in the present publication. Two additional illustrative scenarios for the groups A1FI and A1T are also provided and complete a set of six that illustrates all scenario groups. All are equally sound (IPCC, 2007).

Future SRES scenarios developed by IPCC are comprised of several storylines illustrated in Figure 10.1.

- The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity-building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

- The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient



Source: IPCC, http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=3

Figure 10.1. Schematic illustration of SRES scenarios (HS = harmonized scenario; OS = "uncertainty exploring" scenario)

technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Projections of the future climate are also model-dependent. Tens of general circulation models (GCMs) have been developed in climate research centres all over the world and used to simulate the climatic variations and changes in the past and in the future under different emission scenarios. Comprehensive overview of such results and evaluation of the model skills is given in the IPCC Fourth Assessment Report, WG I, Chapter 8: Climate models and their evaluation (http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter8.pdf). Modelling data for the twentieth century and SRES scenarios for the twenty-first century and supporting documentation are available at http://www.mad.zmaw.de/IPCC_DDC/html/SRES_AR4/index.html and http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php.

The following section focuses on the climatic projections based on multi-model ensemble calculations, which are likely to be more accurate compared with simulations performed with any individual model, and presents a summary of the key IPCC findings.

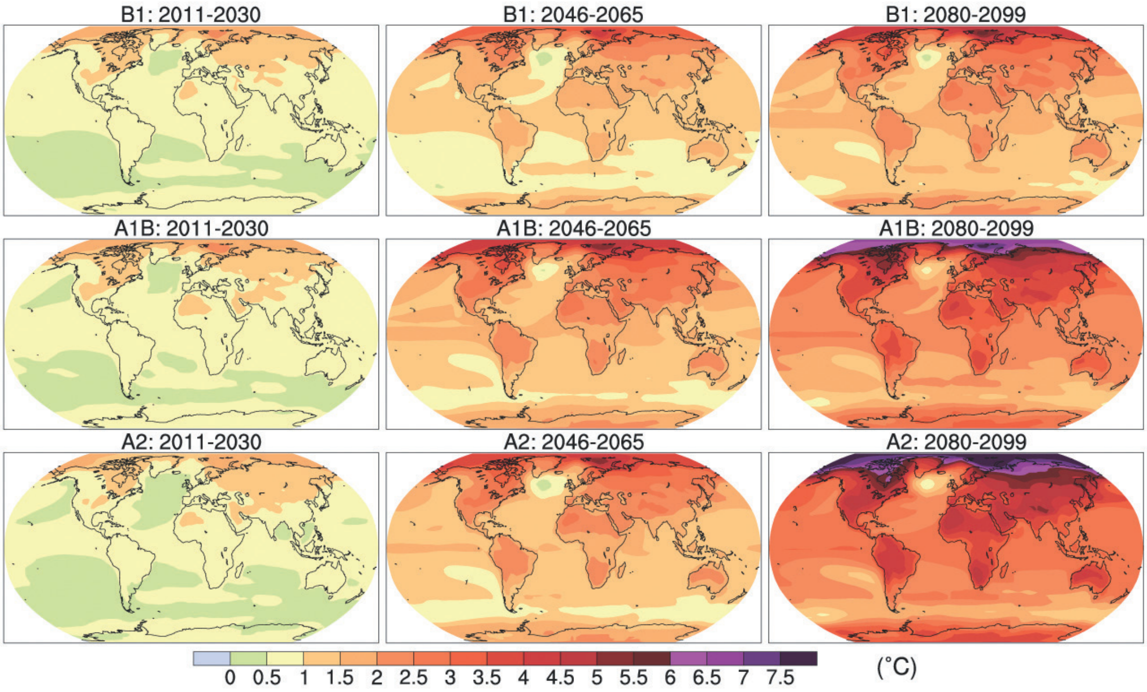
Air temperature projections

Despite the differences in emission scenarios, changes in the global-mean air temperature projected for the early twenty-first century are close to each other. For three different emission scenarios B1, A1B and A2 (hereinafter, for scenario details and designations refer to Nakicenovic and Swart, 2000), the range projected for 2011–2030 global warming compared with 1980–1999 is only 0.05°C, from +0.64°C to +0.69°C (IPCC Fourth Assessment Report, WG I, Chapter 10). By mid-century (2046–2065) projections differ by several tenths of °C (+1.3°C, +1.8°C and +1.7°C). By the late twenty-first century (2090–2099) differences between scenarios become larger, leading to a global temperature range of 2.3°C. Six marker emission scenarios predict the following magnitude of global warming: B1: 1.7°C; A1T: 2.4°C; B2: 2.4°C; A1B: 2.7°C; A2: 3.2°C; and A1FI: 4.0°C (IPCC, 2007, WG I, Chapter 10). Regional temperatures under different emission scenarios are consistent with global projections (Figure 10.2).

Precipitation projections

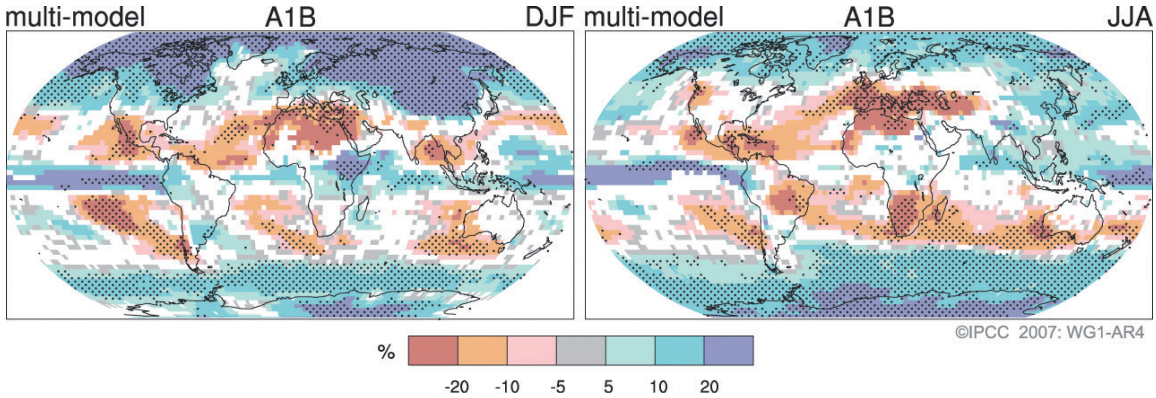
For a future warmer climate, the current generation of models indicates that precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes) and over the tropical Pacific in particular, with general decreases in the subtropics, and increases at high latitudes as a consequence of a general intensification of the global hydrological cycle. Globally averaged mean water vapour, evaporation and precipitation are projected to increase. Intensity of precipitation events is projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation. Even in areas where mean precipitation decreases (most subtropical and mid-latitude regions), precipitation intensity is projected to increase, but there would be longer periods between precipitation events. There is a tendency for drying of the mid-continental areas during summer, indicating a greater risk of droughts in those regions. Precipitation extremes increase more than does the mean in most tropical and mid- and high-latitude areas.

The global map of the A1B 2080–2099 change of annual mean precipitation is shown in Figure 10.3. Overall, precipitation over land increases some 5 per cent, while precipitation over ocean increases 4 per cent, but with regional changes of both signs. The net change over land accounts for 24 per cent of the global mean increase in precipitation, a little less than the proportion of land by area (29 per cent).



Source: IPCC, 2007, Fourth Assessment Report, WG I, Chapter 10

Figure 10.2. Multi-model mean of annual mean surface warming (surface air temperature change, in °C) for the scenarios B1 (top), A1B (middle) and A2 (bottom), and three time periods, 2011–2030 (left), 2046–2065 (middle) and 2080–2099 (right). Anomalies are given relative to the average of the period 1980–1999.



Source: IPCC, 2007, Fourth Assessment Report, WG I, Summary for Policymakers

Figure 10.3. Relative changes in precipitation (in per cent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66 per cent of the models agree in the sign of the change and stippled areas are where more than 90 per cent of the models agree in the sign of the change.

Wetherald and Manabe (2002) provide a good description of the mechanism of hydrological change simulated by GCMs. In GCMs, the global mean evaporation changes closely balance the precipitation change but not locally because of changes in the atmospheric transport of water vapour. Annual average evaporation increases over much of the ocean, with spatial variations tending to relate to those in the surface warming. As found by Kutzbach et al. (2005) and Bosilovich et al. (2005), atmospheric moisture convergence increases over the equatorial oceans and over high latitudes. Over land, precipitation changes tend to be balanced by both evaporation and runoff. Runoff is notably reduced in southern Europe and increased in south-east Asia and in high latitudes.

Use of climate change scenarios

In general, it will be necessary to consider a range of future climate change scenarios from the IPCC projections. It may also be useful to combine these with different scenarios of growth and societal development. The aim will be to check the robustness of future water resources plans against a plausible range of future circumstances so that major investments in water management, such as the construction of new reservoirs or major groundwater exploitation schemes, are soundly based.

In the United Kingdom, the Environment Agency has produced a water strategy for England and Wales that considers four different climate and societal scenarios and their implications for water resources for the twenty-first century (Environment Agency, 2009).

CHAPTER 11. PRESENTATION OF RESULTS

If the results of a water resources assessment are to be incorporated into wider programmes of development planning, land and water management and political decision-making, then it is vital that they are presented in ways that are easily accessible to politicians, the public and professional partners.

In particular, consideration needs to be given to the way that different future scenarios and uncertainties are presented and this may well have to be tailored to different audiences. In the United Kingdom, the Environment Agency has produced a water resources strategy for England and Wales that shows the changes in stress on water resources under different scenarios in the twenty-first century. Both a technical report and a non-technical summary have been produced.

The following are further examples of the presentation of results from water resources assessments:

- Sub-Saharan Africa Hydrological Assessment – West African Countries, Regional Report (World Bank and UNDP, 1992)
- World Water Resources[23] (Shiklomanov, 1998 and Shiklomanov, 2003)
- Environment Agency (United Kingdom)[24] (Environment Agency, 2009)
- Bureau of Meteorology (Australia)[25] (Australian Bureau of Meteorology, 2011)
- Water Resources Assessment of Haiti[26] (US Army Corps of Engineers, 1999)

11.1 MAPS

As shown in many of the above-mentioned publications, maps provide an ideal manner of displaying hydrological information in spatial terms. In this regard, geographical information systems have become a useful and important tool in hydrology for the analysis and presentation of hydrological information. In the hydrologic budget are inputs such as precipitation, surface flows in, and groundwater flows in. Outputs are evapotranspiration, infiltration, surface runoff, and surface/groundwater flows out. All of these quantities, including storage, can be measured or estimated, and their characteristics can be graphically displayed in a GIS and studied. An important element of the use of GIS applications includes access to digital elevation model data which are layered with hydrographic data so that the boundaries of a watershed may be determined. Watershed delineation aids the hydrologist or water resources manager in understanding where runoff from precipitation or snowmelt will eventually drain.

The characteristics of groundwater can also readily be input into GIS for further study and management of water resources.

A further interesting development in this regard is WaterML,[27] a format for the publication of water observations data in XML, typically for use by researchers who need water observations to constrain modelling and forecasting applications. The goal of WaterML v2 is to enable:

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[23] http://webworld.unesco.org/water/ihp/db/shiklomanov/

[24] http://www.environment-agency.gov.uk/research/library/publications/40731.aspx

[25] http://www.bom.gov.au/water/awra/2010/

[26] http://www.sam.usace.army.mil/en/wra/Haiti/Haiti%20Water%20Resources%20Assessment%20English.pdf

[27] http://www.cuahsi.org/his/awra/MorningI/SOA_WebServices_WaterML.pdf

(a) Delivery and consumption of water observations data using systems developed to conform to the agreed standards;

(b) Integration of water observations data with information from closely related domains in environmental sciences, such as geology and meteorology, where Open Geospatial Consortium-conformant systems are being deployed (for example, OneGeology).

11.2 SCALE ISSUES

Water resources assessments may be undertaken at a range of scales, depending on the particular requirements of each study. Thus WRA might be undertaken at a catchment level within a country where local issues predominate and there is little scope for water transfer between catchments. Alternatively, a national scale that includes a number of catchments may be appropriate when long-term development planning and the future location of industrial or agricultural developments are being considered. However, in a continental system, any catchment may in turn be part of a larger multi-country river basin and there are clearly dangers in trying to assess water resources at the state/province/administrative scale rather than treating river basins holistically. Where individual catchments or administrative areas within a larger river basin system are studied separately, there is a clear need for close linkages between studies and harmonization of approaches across the whole river basin to avoid multiple counting of the resource and to ensure that, for example, the same assumptions are applied across the basin.

11.3 TEMPORAL DISTRIBUTION

While noting the issues of spatial presentation and scale, it is essential not to forget the temporal variation of water within all of its forms in the hydrological cycle, from season to season, from year to year and from decade to decade. To present all of this information in a map format may not be either feasible or appropriate and use should be made of tables and graphs to demonstrate this temporal variability. The case studies cited above all show good examples of how this type of information can be presented.

11.4 LINKAGES TO SUSTAINABLE DEVELOPMENT

The availability of water is a key factor for the development of agriculture and industry, as well as a requirement in satisfying the increasing needs of populations as standards of living are improved. Water resources assessment should therefore form a major part of any planning for sustainable development since, by definition, such development requires an assurance that primary resources, including water, will be available to support planned development in the long term. Limitations on water availability will often form a major constraint on development plans. Consequently development should be planned with due consideration of the available water resources.

11.5 LINKAGES TO INTEGRATED WATER RESOURCES MANAGEMENT

As noted in section 1.1, IWRM is a widely approved paradigm, which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Global Water Partnership, Technical Advisory Committee, background paper 4 (2000), available at http://www.gwptoolbox.org/images/stories/gwplibrary/background/tac_4_english.pdf).

Integrated Water Resources Management recognizes that water is required for many different purposes and must consider all demands and threats to an effectively finite resource (in most circumstances). It recognizes the need to balance between upstream and downstream users and it promotes a holistic approach to management and governance that requires coordination between the range of activities that create a demand for water, determine land use and generate water-borne waste. It encompasses economic, social, political and environmental aspects of water management and promotes participatory and consensual decision-making.

Water resources assessment is therefore a significant component of the evidence and analysis required for IWRM. In turn, IWRM provides a framework through which the outcomes and conclusions of a WRA can be implemented across all aspects of water management.

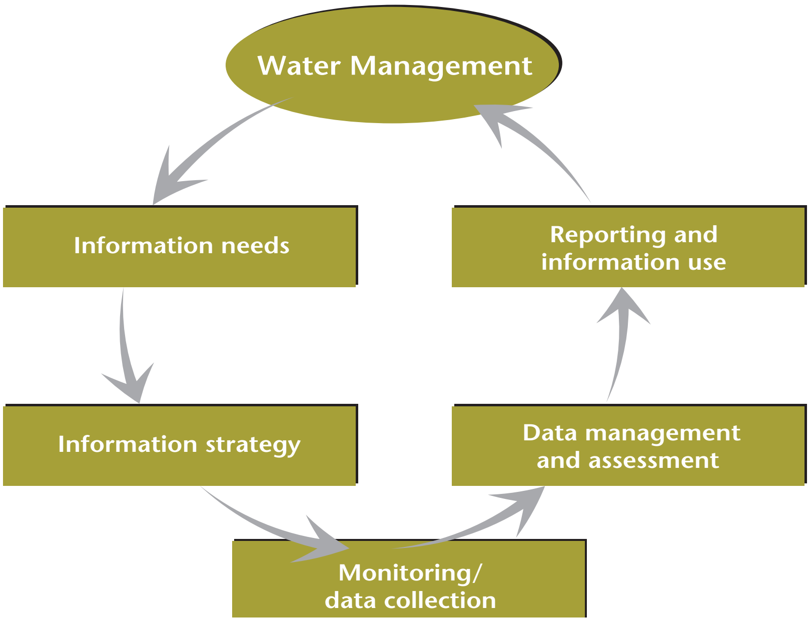
Monitoring and assessment of watercourses follows a sequence of activities, which is shown in Figure 11.1. The outputs produced by each of the elements are used in the consecutive element(s) of the cycle. With iteration of the cycle, the information needs for water management from assessment get fine-tuned or – if policies and/or targets have changed – redefined (UNECE, 2006).

The analysis of water management issues is the basis for specifying the information needs. Information needs are related to the following:

– Uses (for example, drinking water, irrigation, recreation) and functions (maintenance of aquatic life) of the watercourse that put requirements on the quality and availability;

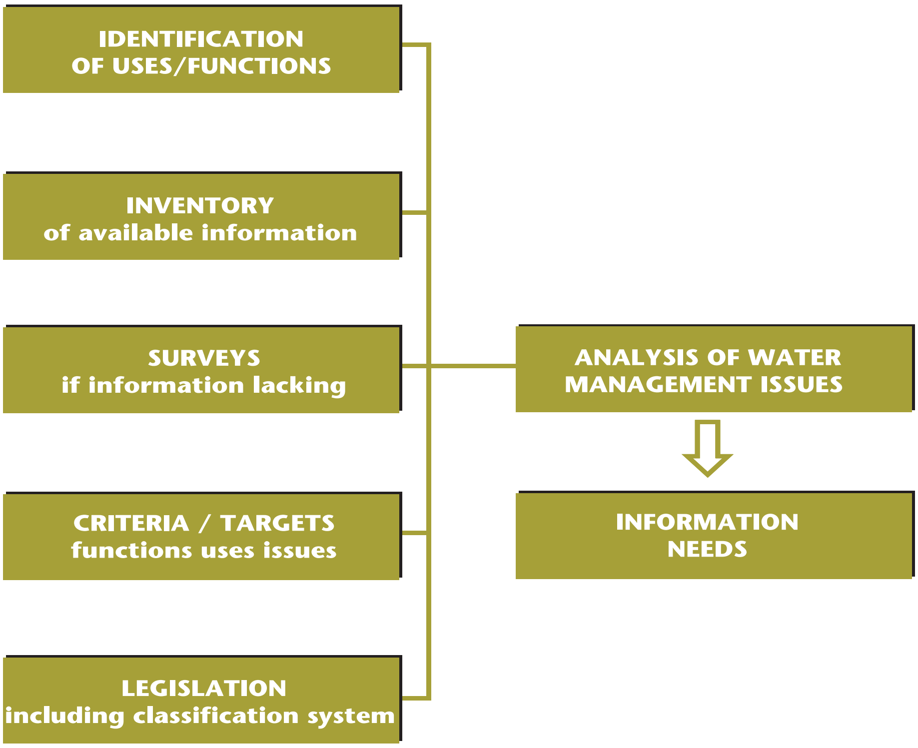
– Issues (for example, flooding, sedimentation, salinization, pollution) that hinder proper use and functioning of the watercourse;

– Measures taken to address the issues or improve the use or functioning of the watercourse, including environmental aspects.



Source: UNECE, 2006

Figure 11.1. Monitoring and assessment cycle



Source: UNECE, 2006

Figure 11.2. Analysis of water management issues

The activities needed to identify issues and priorities include identification of the functions and uses of the river basin, inventories on the basis of available (and accessible) information, surveys (if information is lacking), identification of criteria and targets, and evaluation of the water legislation to identify provisions that are important for monitoring and assessment (Figure 11.2).

Support must be provided so that specified information on water resources assessment can be further developed in terms of variables to be monitored/assessed, time frame and frequencies.

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APPENDIX I. INTERNET SOURCES OF DATA

Global level

The main datasets available from the Internet are presented in the table below, with the name of the providing data centre and the corresponding URL. Note that depending on the dataset, it will be available free of charge, for an administrative fee, or after having signed a user agreement. Some datasets are restricted to research or non-commercial use.

Datasets *Categories of information*	*Centre/providing company*	*Current Internet link*
1. Biophysical data		
AQUASTAT – Land use and population – Climate and water resources – Water use, by sector and by source – Irrigation and drainage development – Environment and health	**FAO** Food and Agriculture Organization of the United Nations	http://www.fao.org/AG/AGL/aglw/aquastat/main/index.stm
FAOSTAT – Land use and irrigation, fertilizer and pesticides statistics	**FAO** Food and Agriculture Organization of the United Nations	http://faostat.fao.org/
– Land cover – Population density – Biodiversity for 154 basins and sub-basins around the world	**IUCN** water atlas World Conservation Union	http://www.waterandnature.org/en/resources/publications/thematic-collection/facts-figures/watersheds-world
Gridded population of the world	**SEDAC** Socioeconomic Data and Applications Centre	http://sedac.ciesin.columbia.edu/gpw/
2. Topographic data		
TOPO30 **STRM** – Elevation data (land) **HYDRO1k** – Streams, drainage basins	**USGS** United States Geological Survey	http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/Elevation_Products
ETOPO5 and **ETOPO2** – Global relief (land and oceans)	**NGDC** National Geophysical Data Center	http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html
3. Climate data		
– Precipitation, temperatures, pressure…	**CRU** Climatic Research Unit	http://www.cru.uea.ac.uk/
Global precipitation analysis	**GPCC** Global Precipitation Climatology Centre	http://gpcc.dwd.de
4. River flow data		
– Water fluxes into the oceans – Discharge statistics – Composite runoff fields – Global Terrestrial Network for River Discharge (GTN-R) …	**GRDC** Global Runoff Data Centre	http://grdc.bafg.de

Datasets *Categories of information*	*Centre/providing company*	*Current Internet link*
5. Groundwater data		
GGIS Global groundwater information system – Aquifer characteristics – Groundwater quantity – Groundwater quality – Groundwater development – Groundwater problems ….	**IGRAC** International Groundwater Resources Assessment Centre	www.igrac.nl
6. Water quality data		
GEMSTAT – Surface water and groundwater quality datasets	**GEMS Water,** UNEP	http://www.gemstat.org/
7. Water resources data		
GRID Global Resources Information Database – Freshwater – Climate – Population …	**UNEP** United Nations Environment Programme	http://www.grid.unep.ch/ http://geodata.grid.unep.ch/
Earthtrends – Water resources and freshwater ecosystems	**WRI** World Resources Institute	http://www.wri.org/project/earthtrends/

Regional level

Examples of datasets available in Europe (EU)

Datasets *Categories of information*	*Centre/providing company*	*Current Internet link*
Reference waterbase – Status and quality of Europe's rivers, lakes and groundwater bodies **Waterbase** – Status and quality of Europe's rivers, lakes, groundwater bodies and transitional, coastal and marine waters, and on the quantity of Europe's water resources **CORINE** – Land cover	**EEA** European Environment Agency	http://www.eea.europa.eu/data-and-maps/
EUROSTAT – Water, land use, climate statistics	**EC** European Commission	http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/
WISE Water Information System for Europe – Catchments – River segments	**JRC** Joint Research Centre	http://water.europa.eu/ http://agrienv.jrc.ec.europa.eu/index.htm

APPENDIX II. REMOTE-SENSING SATELLITE SYSTEMS

Satellite system	*Sensors*[1]	*Spectral coverage*[1, 2]	*Spatial resolution*[3]	*Temporal resolution*[4] *(repeat cycle)*	*First satellite launched*
Medium resolution					
EOS (Earth Observation System) United States	MODIS (moderate-resolution imaging spectroradiometer) attached to Terra and Aqua satellites in EOS	VIS, NIR, SWIR, MWR, TIR Panchromatic and multispectral	250–1 000 m	2 days	1999
ENVISAT	MERIS	VIS, NIR Panchromatic and multispectral	200–1 200 m	—	2002
ADEOS-2	GLI (global imager)	VIS, NIR, SWIR, TIR	250–1 000 m	41 days	2002
High resolution					
Landsat United States	MSS (multispectral scanner) TM (thematic mapper) EMT+ (enhanced thematic mapper plus)	VIS, NIR, SWIR, TIR Panchromatic and multispectral	15 –120 m	16 days	1984
SPOT 1-4 France	HRV (high-resolution visible) HRVIR (high-resolution visible IR)	VIS, NIR (HRV 4 band, HRVR 5 band) Panchromatic and multispectral	10 –20 m	26 days	1986
Earth Observing-1 (EO-1) United States	Hyperion (high-resolution hyperspectral imaging instrument) ALI (advanced land imager) AC (atmospheric corrector)	VIS, NIR, SWIR Panchromatic and multispectral	30 m	16 days	2000
Indian Remote Sensing Satellite (IRS) India	LISS (linear imaging self scanning sensor): multispectral 4-channel sensors PAN (single channel panchromatic sensor) WIFS (wide field sensor)	VIS, NIR Panchromatic and multispectral	36 – 72 m <10 –189	22 days	—
RESURS Russian Federation, Sweden	MSU-SK (multispectral scanner of moderate resolution with conical scanning) MSU-E (high-resolution multispectral scanner with electronic scanning)	VIS, NIR Panchromatic and multispectral	170 m	21 days	1985
Very high resolution					
IKONOS United States	Panchromatic and multispectral sensors	VIS, NIR Panchromatic and multispectral	1–4 m	1.5–2.9 days	1999
EROS-A1 Israel, United States	—	Panchromatic	1.8 m	—	2000
Quickbird-2	—	VIS, NIR Panchromatic and multispectral	0.6–2.5 m	—	2001

Satellite system	*Sensors*[1]	*Spectral coverage*[1, 2]	*Spatial resolution*[3]	*Temporal resolution*[4] *(repeat cycle)*	*First satellite launched*
SPOT 5	HRG (high resolution geometry)	VIS, NIR, SWIR Panchromatic and multispectral	2.5–20 m	26 days	2002
Microwave remote-sensing satellites					
ERS-1,2 SAR (synthetic aperture radar)	AMI (active microwave instrument): RA-1 (radar altimeter) ATSR (along track scanning radiometer) GOME (Global Ozone Monitoring Experiment) passive spectrometer	Active and passive microwave	30 m	35 days	1991
JERS-1 SAR (synthetic aperture radar) Japan	SAR (synthetic aperture radar) OPS (optical sensor)	Active and passive microwave	18 m	44 days	1992
ENVISAT ASAR (advanced synthetic aperture radar)	SAR (synthetic aperture radar) with alternating polarization mode (HH and VV, or HH and HV, or VV and VH)	—	30–150 m	—	2002
RADARSAT SAR (synthetic aperture radar) Canada	SAR (synthetic aperture radar)	Active and passive microwave	11–100 m	24 days	1995

Notes:

1. The sensors and spectral coverage are what are available now; they may not all be available for the full length of the archive.
2. Visible (VIS), near infra-red (NIR), short-wave infra-red (SWIR), microwave radiometer (MWR) and thermal infra-red (TIR).
3. The different sensors provide datasets at different spatial resolutions so not all data types are available at the finest resolution listed.
4. The temporal resolution is the highest frequency available, but not all areas are available at the same frequency.

Only satellite systems that are still active are listed in the table; low-resolution satellite systems are not listed as they are of limited value to the assessment of water resources.

Surface water, soil moisture

Radar altimetry data from satellite systems can measure the levels of selected lakes and large rivers in absolute terms with time intervals of 10 days (TOPEX/POSEIDON, JASON) or 35 days (ERS and ENVISAT), generally with an accuracy about 10-cm root mean square, although accuracy depends on conditions (Chelton et al., 2001; Berry et al., 2005,). JASON Interim Geophysical Data Record datasets are available via ftp at http://podaac.jpl.nasa.gov/dataset/JASON-1_IGDR.

In view of the poor density of raingauges in many parts of the world and variations in data availability and consistency, methods have been developed to use easily available multispectral satellite images to improve determination of spatial precipitation. An overview is given by Collier (2000).

For estimation of daily precipitation, use is made of the visual bands to detect cloud patterns using reflectivity and the thermal band is used for obtaining the temperature of clouds – the “cold cloud duration" and temperature thresholds are important parameters. Despite the relatively low accuracy of daily precipitation measurement by multispectral satellite data only, for large areas, use of satellite data always improves spatial precipitation estimates if gauge density is low. The Famine Early Warning Systems (FEWS) (http://www.fews.net/) offers 10-day precipitation data for all of Africa. The Tropical Rainfall Measuring Mission (TRMM) was the first satellite with the specific purpose of measuring precipitation in the tropics by employing active radar. TRMM products are archived and distributed by the Goddard Distributed Active Archive Center (http://trmm.gsfc.nasa.gov/data_dir/data.html).

Where snowmelt is a major source of water and snow depth surveys are not made systematically, indirect methods using multispectral images can provide essential information on snow cover. Studies have been made to use multi-frequency passive radar for snow water equivalent determination. The coarse resolution (about 25 km) of the passive radar systems, such as NIMBUS 7 SMMR or SSM/I, restrict the use for small mountain catchments, but they are used for real-time snow and runoff forecasts by specialized centres in countries (for example, the United States and Canada) where extensive snowpacks constitute a major source of water and may cause flooding. For more information, see reviews by König et al. (2001) and Hall et al. (2005).

A major step forward in making water budgets or water balances is the ability to map the actual evapotranspiration using multiple satellite measurements. This mapping is an expanding research field and early approaches had the difficulty that most remote-sensing evapotranspiration algorithms required too much input data. In recent years, progress has been made in adjusting the algorithms for general use with minimum data requirement. The potential for improved satellite-based evapotranspiration mapping has been applied and validated in several studies at varying scales.

Remote sensing can contribute substantially to the study of the dynamics and water budgets of large wetlands in various parts of the world. The variable extent and water levels of the wetlands can be determined accurately and linked to inflow/outflow, the main vegetation types can be classified and also the evapotranspiration of the wetland can be assessed. In many cases, the historical monitoring record can only be established by time series of multispectral images, starting with the Landsat MSS images from 1972, supplemented by earlier aerial photography. Thermal images at mid-day and nighttime proved to be useful in wetland mapping by making use of the thermal inertia of wet and dry land (Travaglia et al., 1995). In other cases, sequential radar images can be used, because of the cloud penetration capacity of active radar, in studying the dynamics of marshes (for example, Travaglia and Macintosh, 1997). Radar images have also been used for mapping water extent under vegetation canopies (Hess et al., 1995).

For many large irrigation schemes areas of various crops can be established by multispectral classification and if done with adequate sample sets based on ground truth, over 75 per cent of crops can generally be classified appropriately. Soil salinization often occurs due to irrigation practices in the absence of proper drainage, and such areas in their final stage can be identified using multispectral images (Metternich and Zinck, 2003). With additional information and using crop responses, as measured by satellite data, the earlier stages of salinization can also be detected. Satellite data also offer new possibilities in assessing water requirements, irrigation performance indicators and crop yield prediction and yield per m^3 water, as discussed by Bastiaanssen (1998) and Menenti (2000*a*, 2000*b*).

Soil moisture

Remote sensing offers a possibility to obtain the pattern of soil moisture; for an overview, see Engman (2000). The theoretical basis for measuring soil moisture by microwave techniques is based on the large contrast of the dielectrical properties of liquid water and of dry soil, and the dielectric constant influences the backscatter signal of the radar pulse of the active radar systems. However, a problem is that surface roughness, depth of measurement (restricted to the uppermost soil layer) and vegetation also affect the sensed characteristics, and these effects vary with instrument parameters, incidence angle and frequency of the radar system used.

The active radar satellite systems with wavelengths suitable for soil moisture with resolutions of 20 to 30 m are the European Space Agency's ERS-1 and -2, the Japanese JERS-1 SAR and the Canadian RADARSAT, although aircraft systems offer even higher resolutions. Although successful experiments have been carried out (Engman, 2000), the studies are in the research domain and data availability limits applications.

A step forward is the global, coarse-resolution, soil moisture data (25–50 km) derived from measurements acquired with scatterometers onboard the ERS-1 and ERS-2 satellites (since 1991, and their successor) and the three MetOp satellites (2006–2020), as discussed by Scipal et al. (2005). The passive microwave radiometers and scatterometers allow better accounting for the confounding effects of vegetation and surface roughness, which affect both active and passive microwave systems. The regional maps related to soil moisture are available on the Internet at http://www.ipf.tuwien.ac.at/radar/index.php?go=ascat. Multispectral and thermal satellite data have been used to estimate soil hydraulic functions, through evapotranspiration (Jhorar et al., 2002).

Groundwater

For a comprehensive review of this topic area and detailed guidance on the methods, please refer to Meijerink et al. (2007).

Seasonally fluctuating groundwater levels or long-trend declining groundwater levels in aquifers cause deformation at the surface if the aquifer system has highly compressible sediments. Satellite radar data can be used to detect such deformation of the land surface. Very small changes in elevation (on cm scale or even fractions of cm under ideal conditions) of the terrain surface can be detected and mapped by using three SAR images of the same area acquired during different overpasses to generate two interferograms. The arithmetic difference of the two interferograms is taken to produce a differential interferogram.

Land subsidence due to pumping and also uplift of the land surface attributed to recharge of groundwater in an aquifer has been detected using time series of radar images over a period of several years. The resulting patterns of deformation, with groundwater-level data, have provided new insights in the behaviour of the groundwater and allowed modelling improvements for land subsidence and groundwater flow (Hoffman et al., 2003).

Concentrated discharge of groundwater into the sea of coastal areas, through karstic conduits of limestone terrain or large permeable faults and fractures, can be detected on thermal imagery (for example, Stefanouli and Tsombos, 2004). Generally, aircraft sensors are used because of their high spatial resolution and the ability to select the best time for a temperature contrast between the upwelling fresh groundwater (low density) and the saline sea water (high density), but thermal satellite images have also been used.

Temperature contrasts in rivers on thermal imagery have also been used to detect river stretches with strong groundwater discharge, while groundwater emergence in exfiltration areas of groundwater flow systems have been recognized in some areas by the lower temperature of the wet soil.

Remote-sensing images are important for groundwater studies in hard rock terrain where groundwater is limited to fractures and weathered zones. Potential water-bearing fractures are identified on the images as lineaments, while a separate vegetation index image can prove whether the lineament supports phreatophyte vegetation or not. See the special issue of the Geological Society, United Kingdom (Wright and Burgess, 1992).

Relative aquifer recharge patterns can be obtained based on factors derived from remote sensing such as vegetation cover, fracture density, presence and extent of sandy and gravely wadi beds with ephemeral transmission losses and the interpreted nature of surface material and depression areas.

APPENDIX III. THE PENMAN FORMULA

The Penman formula:

$$Ep = \frac{\Delta}{\Delta + \gamma}\frac{ho - G}{HV} + \left\{ \frac{\gamma}{\Delta + \gamma} f(v)(e(a) - e(d)) \right\} \tag{III.1}$$

where Ep = potential evaporation in mm; Δ = slope of the saturation vapour pressure curve in kPa/°C; γ = psychometric constant in kPa/°C; ho = net radiation in MJ/m^2; G = soil heat flux in MJ/m^2; HV = latent heat of vaporization in MJ/kg; $f(V)$ = function of the wind velocity in mm/day kPa; $e(a)$ = saturation vapour pressure at mean air temperature in kPa; and $e(d)$ = vapour pressure at mean air temperature in kPa.

The latent heat associated with vaporization is estimated as a function of temperature:

$$HV = 2.5 - 0.0022|T \tag{III.2}$$

where T = average daily temperature in °C.

The saturation vapour pressure is also estimated as a function of temperature, using the following equation:

$$e(a) = 0.1e^{\left(54.88 - 5.03 In(T = 273) - \frac{6791}{T + 273}\right)} \tag{III.3}$$

The vapour pressure is estimated as a function of the saturation value and the relative humidity, RH, expressed as a fraction:

$$e(d) = a(a)RH \tag{III.4}$$

where RH = vapour pressure in kPa.

The slope of the saturation vapour pressure curve is estimated using the following equation:

$$\Delta = \frac{e(a)}{T + 273}\left\{ \frac{6791}{(T + 273 - 5.03} \right\} \tag{III.5}$$

The psychometric constant is calculated using the following equation:

$$\gamma = 6.6e^{10^{-4}} PB \tag{III.6}$$

where PB = barometric pressure in kPa

The barometric pressure is estimated as a function of the elevation using the following equation:

$$PB = 101 - 0.0115Z| + 5.44e^{10^{-7}}\sqrt{Z} \tag{III.7}$$

where Z = site elevation in m (above sea level).

The net radiation is calculated using the relationships proposed by Campos (2002), which are described in the following section:

$$Rn = Ri(1 - r) - Rnl \tag{III.8}$$

where Rn = net radiation; Ri = incident radiation; r = albedo (r = 0.05 for large water bodies); and Rnl = net long-wave radiation.

All the variables are expressed in cal/cm^2/day, except the albedo, which is non-dimensional.

The incident radiation is determined as follows:

$$Ri = \mathrm{R}_E\left(a + b\frac{n}{N}\right) \qquad \text{(III.9)}$$

where R_E = radiation in the exosphere, cal/cm^2/day; a = empirical constant; b = empirical constant; n = average daylight hours, hr; and N = maximum possible number of daylight hours, hr.

$$\begin{aligned} a &= 0.290\cos\varphi \\ b &= 0.550 \\ N &= A + B\left\{sen\left(30nm + 83.5\right)\right\} \end{aligned} \qquad \text{(III.10)}$$

where A and B = constants which are a function of the latitude of the areaφ; and degrees *nm* = number of the month (1 for January and 12 for December); these are estimated using the following expressions:

$$A = 12.09086 + 0.00266\varphi$$

$$B = 0.2194 - 0.06988\varphi$$

The radiation in the upper atmosphere or exosphere is calculated using the following equation:

$$R_E = b_0 o + b_1\,(\varphi - 10)(\varphi - 20) + b_3\,(\varphi - 10)(\varphi - 20)(\varphi - 30) \qquad \text{(III.11)}$$

Twelve such equations exist, depending on the month in question. The table below illustrates the values of b for each corresponding month.

Month	b_0	b_1	b_2	b_3
January	760	–12	–0.075	0.0016666670
February	820	–9	–0.100	0.0008333333
March	875	–5	–0.125	0.0008333333
April	895	0	–0.125	–0.0008333336
May	890	4	–0.100	–0.0025000000
June	875	6	–0.100	–0.0016666670
July	880	5	–0.100	–0.0008333333
August	890	2	–0.125	–0.0008333336
September	880	–2.5	–0.150	0.0008333336
October	840	–8	–0.075	–0.0008333333
November	780	–11.5	–0.025	–0.0033333340
December	740	–12.5	–0.075	0.0033333340

Source: UNESCO, 2008 (northern hemisphere)

The net long-wave radiation is calculated as follows:

$$Rnl = \sigma T_{2|}^{4}(0.56 - 0.08\sqrt{e_2})\left(0.10 + 0.9\frac{n}{N}\right) \qquad \text{(III.12)}$$

where T_2 = air temperature at an altitude of 2 m, °K (°K=°C+273); σ = Stefan–Boltzmann Constant, equal to $1.17(10_{-7})$ ly/°K_4/day; e_2 = vapour pressure at an altitude of 2 m, millibars; and $\frac{n}{N}$ = relative hours of sunshine, obtained from equation III.9.

The result of the net radiation is expressed in cal/cm^2/day. For this reason it is necessary to convert to MJ/m^2 to be able to substitute accordingly in Penman's equation. Therefore, the following relationship is used:

$$ho = 0.418680Rn \qquad \text{(III.13)}$$

The value of the soil heat flow variable, G, is so small that it is considered to be zero.

Finally, the wind function, $f(V)$, of equation III.1 is estimated using the following relationship:

$$f(V) = 2.7 + 1.63V \qquad \text{(III.14)}$$

where V is the average daily wind speed at an altitude of 10 m, expressed in m s^{-1}.

APPENDIX IV. RUNOFF VOLUME CALCULATION USING THE NRCS CURVE NUMBER

(NRCS, 1985)

The relationship between precipitation depth P and runoff volume V as a depth equivalent is:

$$V = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{if} \quad P \geq 0.2S \quad \text{or} \quad V = 0 \quad \text{if} \quad P < 0.2S$$

$$S = \frac{25{,}400}{CN} - 245 \quad \text{(V, P, S in mm)} \qquad \text{(IV.1)}$$

or

$$S = \frac{1{,}000}{CN} - 10 \quad \text{(V, P, S in inches)} \qquad \text{(IV.2)}$$

where V = runoff depth; P = precipitation; S = maximum potential retention after runoff begins; and CN = curve number.

V is multiplied by the drainage area to obtain flow volume. S represents an upper limit on the amount of water that can be abstracted by the watershed through surface storage, infiltration and other hydrologic abstractions. S is expressed in terms of a curve number (CN), which is a dimensionless watershed parameter ranging from 0 to 100. A CN of 100 represents a limiting condition of a perfectly impervious watershed with zero retention and thus all of the precipitation becoming runoff. The CN may be estimated from empirical information developed by the NRCS relating the CN to watershed soil type, land cover and use, and antecedent moisture conditions (Warbs, 2006).

To account for the travel time and the attenuation of a volume of water imposed on the catchment by a precipitation event, an accounting through time at the catchment outlet must be performed. This step is usually accomplished by the use of a unit hydrograph, which describes the temporal distribution of runoff leaving the catchment. The unit hydrograph is constrained by the principal of continuity of mass in the following manner (WMO, 1994):

$$V = Q(t)dt \qquad \text{(IV.3)}$$

where $Q(t)$ = the instantaneous discharge rate, $Q(t)$ defines a curve whose shape correctly represents the catchment characteristics; t = time; and V = the runoff volume.

For more information, please contact:

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