Hydrometeorology

Kevin Sene

Hydrometeorology

Forecasting and Applications

Springer

Kevin Sene
United Kingdom

ISBN 978-90-481-3402-1 e-ISBN 978-90-481-3403-8
DOI 10.1007/978-90-481-3403-8
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2009939535

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

This book provides an introduction to recent developments in the area of hydrometeorological forecasting, with a focus on water-related applications of meteorological observation and forecasting techniques.

The Encylopaedia Britannica defines hydrometeorology as a branch of meteorology that deals with problems involving the hydrologic cycle, the water budget and the rainfall statistics of storms…(*continued*). The topic spans a wide range of disciplines, including raingauge, weather radar, satellite, river and other monitoring techniques, rainfall-runoff, flow routing and hydraulic models, and nowcasting and Numerical Weather Prediction techniques. Applications include flood forecasting, drought forecasting, climate change impact assessments, reservoir management, and water resources and water quality studies.

The emphasis in this book is on hydrometeorological forecasting techniques, which are usually distinguished from prediction or simulation studies in that estimates are provided for a specific time or period in the future, rather than for typical past, current or future conditions. Often this requires the use of real-time observations and/or forecasts of meteorological conditions as inputs to hydrological models. The availability of information on current conditions also means that – particularly for short lead times – data assimilation techniques can be used to improve model outputs; typically by adjusting the model inputs, states or parameters, or by post-processing the outputs based on the differences between observed and forecast values up to the time of the forecast.

Recent developments in meteorological forecasting techniques have significantly improved the lead times and spatial resolution of forecasts, with single-valued (deterministic) forecasts typically showing skill several days or more ahead, and probabilistic forecasts sometimes providing useful information for periods of weeks ahead or longer. An improved understanding of large-scale oceanic and atmospheric features, such as the El Niño-Southern Oscillation (ENSO), is also improving the skill of forecasts at longer lead times.

These improvements are increasingly reflected in the performance of the operational hydrological models used for forecasting the impacts of floods, droughts and other environmental hazards. Of course, at lead times from a few days ahead or more, it may only be possible an indication of the location and timing of events, and this inherent uncertainty is discussed in several chapters. In particular, ensemble forecasting techniques are increasingly used in hydrological forecasting, and have been standard practice in meteorological forecasting for more than a decade.

Another key consideration with hydrometeorological forecasts is that the information provided is usually used for operational decision-making. This can range from decisions within the next few hours on whether to evacuate people from properties at risk from flooding, through to longer-term decisions such as on when to plant and harvest crops, or to impose water-use restrictions during a drought event. Forecasting models are therefore often embedded in early warning and decision support systems, which may include detection, warning dissemination and emergency response components. Several examples are provided for flood forecasting, drought forecasting and water supply, irrigation and hydropower applications, with techniques ranging from simple threshold-based approaches, such as issuing a flood warning when river levels pass a pre-defined value, through to probabilistic systems which attempt to provide optimal solutions subject to a range of operational, technical, economic and other constraints.

The book is presented in two main sections as follows:

- Part I – Techniques – which discusses a range of observation and forecasting techniques in meteorology and hydrology, together with methods for demand forecasting and decision-making
- Part II – Selected Applications – which discusses a range of applications in forecasting for floods, drought, flow control, environmental impacts and water resources

A glossary provides a reference to the terminology which is used, and gives alternative names where the usage differs between countries (for example, catchments, river basins, drainage basins and watersheds).

The forecasting techniques which are discussed include nowcasting, Numerical Weather Prediction and statistical approaches, conceptual, distributed and data-driven rainfall-runoff models, and hydraulic models for forecasting the response of rivers, reservoirs and lakes. In some applications, demand forecasts are also required, such as the water requirements for water supply, irrigation and hydropower generation, and methods are discussed for a range of timescales, from short-term hydropower scheduling through to long term assessments of water requirements for investment planning. A wide range of detection techniques is also discussed, although specific brands of software and instrumentation and other types of equipment are generally not considered.

UK Kevin Sene

Acknowledgements

This book has benefited from discussions with many people. Following some time working in fluid mechanics, I moved to the Centre for Ecology and Hydrology in Wallingford. There, I had the opportunity to work on a wide range of research and consultancy projects, with much of this work overseas. Moving to a large engineering consultancy, my focus turned to real-time applications, leading to publication of the book ‘Flood Warning, Forecasting and Emergency Response’ in 2008.

For this book, many people have helped with reviewing short extracts of text, and providing permission to use figures and to include a discussion of their projects. Many organizations now also place the findings from research and project work in the public domain, which has proved to be a valuable resource. Throughout, the publisher and myself have tried to determine the original source of material and to provide appropriate citations, although we apologise if there have been any unintentional errors.

The book includes a number of short case studies in the form of text boxes, and text linked to figures, and the following people have helped by providing comments on these descriptions and/or permission to use the associated figures, including (with the box numbers shown in brackets): E. Blyth (11.4), J. Bromley and colleagues (8.2 and 11.2), M. Brown (8.3), R. O’Callaghan, P. Carter and Y. Chen (2.2), G. Charchun (5.3; part), R. Hartman (1.2, 9.2), M. Huttunen and colleagues (7.3, 10.1 and text linked to Fig. 10.7), M. McCartney (11.1), C. McPhail (10.4), G. Munoz (5.2), C. Obled (3.2), M. Potschin and R. Haines-Young (6.2), P. Sayers (6.1), E. Sprokkereef (7.2, 10.2), J. van Steenwijk (10.2), and M. Svoboda (8.1). I would also like to thank Clive Pierce for providing a significant re-write of Box 3.1, and Frank Weber for the description on which Box 11.3 is based. Heiki Walk also provided the text on short-term load forecasting in Box 5.3. Other people who allowed figures to be used (with the figure numbers shown in brackets) include B. Davey and M. Keeling (1.3), Y. Chen (2.2 and part of 2.8 and 9.1), T. Love (2.6), D.-J. Seo (1.1, 6.5), K. Stewart (2.9, 2.10), C. Stow and colleagues (10.5, 10.6), and A. Troccoli and M. Harrison (6.3).

I would also like to thank my colleagues Marc Huband, Yiping Chen and Ben Piper for reviewing early drafts of some of the case studies, and Oliver Taylor for his general support. Finally, from Springer, I am grateful to Robert Doe and Nina

Bennink for their help and advice throughout the process of writing and publishing the book.

Where figures are from external sources, this is acknowledged in the captions; however, for completeness, the following figures (including those mentioned above) are from publications, presentations or websites produced by the following organisations:

- Australian Bureau of Meteorology (Fig. 3.4)
- BC Hydro (Figs. 4.10, 5.7, 5.8, 11.6–11.8)
- Cabinet Office (Fig. 3.1)
- CEM, University of Nottingham (Fig. 6.6)
- Centre for Ecology and Hydrology, Wallingford (Figs. 10.2, 11.9)
- ECMWF (Figs. 3.6–3.8)
- Environment Agency (Figs. 2.1, 2.2, 2.8, 4.11, 5.1, 7.4, 8.5, 9.1 (part), 11.5)
- Finnish Environment Institute (Figs. 7.10, 10.1, 10.7)
- Food and Agriculture Organization (Figs. 5.2, 5.4, 5.5)
- Governor's Office of Homeland Security and Emergency Preparedness (Louisiana) (Fig. 1.10)
- HR Wallingford (Fig. 6.4)
- Institut National Polytechnique de Grenoble (Fig. 3.9)
- International Water Management Institute (Fig. 11.1)
- Joint Research Center (Fig. 8.6)
- Met Office (Figs. 1.4, 1.9, 2.3 (part), 2.5, 3.1, 3.5)
- National Drought Mitigation Center (Figs. 1.2, 8.1, 8.2)
- NOAA, Great Lakes Environmental Research Laboratory (Figs. 10.5, 10.6 and Table 10.2)
- NOAA, National Weather Service (Figs. 1.1, 1.5–1.8, 2.4, 2.6, 2.9 (part), 6.5, 9.6, 9.7)
- Office of Science and Technology (Fig. 7.2)
- Open University (Fig. 1.3)
- Rijkswaterstaat (Figs. 7.6, 7.7, 9.3, 10.3)
- SEPA (Fig. 10.8)
- Springer (Figs. 2.7 (part), 4.1, 4.3 (part), 4.4, 4.8, 4.9, 6.3, 7.3, 7.5, 7.8, 9.1 (part), 9.4 (part), Tables 7.3, 8.6, 9.2 (adapted) and 9.3 (adapted))
- Tennessee Valley Authority (Fig. 5.6)
- Urban Drainage and Flood Control District (Figs. 2.9 (part), 2.10)
- United Utilities (Figs. 8.3, 8.4, 11.3, 11.4)
- U.S. Environmental Protection Agency (Fig. 9.8)

Contents

Chapter 1
Introduction

Abstract Hydrometeorological forecasts can be used to assist with emergency management, routine operations, and for longer-term strategic planning. The range of potential applications is large, and can include flood warning, drought forecasting, reservoir operations, hydropower and irrigation scheduling, pollution control, and river basin management. Users may require information in a range of formats, and at different lead times and spatial scales, meaning that the techniques which are used need to be adapted to each application. The approach to interpretation of forecasts can also vary widely, ranging from visual inspection of outputs through to risk-based and probabilistic decision support systems. This chapter presents a general introduction to these topics, and to some of the applications which are presented in later chapters. The areas which are discussed include user requirements for forecasts, approaches to decision-making, and the general techniques which are used in meteorological and hydrological forecasting, and for demand forecasting for water supply, irrigation and energy generation.

Keywords Hydrometeorology · Meteorology · Hydrology · Hydrologic · Demand · Forecast · Lead time · Decision support · Risk-based

1.1 Forecasting Applications

Hydrometeorological forecasts usually aim to provide an estimate of future catchment conditions, based on recent and forecast meteorological conditions, and hydrological observations. Some potential applications include flood warning, drought forecasting, the response to pollution incidents, hydropower operations, and longer-term planning for water resources, irrigation and flood risk management.

Forecasts can be required at a range of timescales, ranging from a few hours or less in flood warning applications, through to many years or decades ahead for long-term strategic planning. In hydrology, the distinction is often made between the following timescales for decision-making:

K. Sene, *Hydrometeorology*, DOI 10.1007/978-90-481-3403-8_1,

- Tactical or Emergency – including flood warning, hydropower generation, irrigation scheduling, water supply operations, and predictive control for urban drainage systems
- Seasonal or Intraseasonal – including drought forecasting, planting/harvesting of crops, water resources management, and annual snowmelt forecasts
- Strategic or Inter-Annual – including river basin management, investment planning, climate change impact assessments, and the operation of reservoir and groundwater systems with large over-year storage

The boundaries between these timescales are not clear-cut and depend on the application.

The scale at which forecasts are ideally required is also an important consideration, and some typical categories include the field (or plot) scale in irrigation applications, through to farm, community, catchment, regional, continental and global scales. The focus also varies between users; for example, emergency managers and urban drainage system operators may be interested in information at a town or city scale whilst, for a wide-spread disaster, international disaster relief organizations are often interested in information across many countries.

The forecasting requirements for lead-time and spatial scale therefore vary and Table 1.1 provides an indication of the requirements for some of the applications which are described in later chapters. Some more detailed examples are provided – for example – by Meinke and Stone (2005) and Bellow et al. (2008), for agricultural applications, by Sene (2008), for flood warning applications, and by the National Research Council (National Research Council 2006) for a wide range of potential end-users in the USA. Here, a subcatchment is defined as the area to the point at which the forecast is required, which might be some way inland from the river outlet (and is often called a Forecasting Point, Flood Forecast Point, or Water Supply Point in real-time forecasting applications).

Of course, the lead time which can be provided in practice is constrained by factors such as catchment response times, and the accuracy of meteorological forecasts at the required lead times. Internationally, there is also much development work underway to develop seamless forecasts valid for a range of lead times, for a range of applications, with consistent estimates of uncertainty throughout. For example, Fig. 1.1 illustrates the range of potential benefits for applications in the USA using this approach (Seo and Demargne 2008).

It is also worth noting that, at longer lead times, the distinction between forecasts and simulation modeling becomes less clear-cut. However, forecasts are usually considered to apply to a specific date or time interval (no matter how uncertain), whilst simulation or prediction studies typically consider representative past, current and/or 'future' conditions (e.g. Nemec 1986, Tallaksen and van Lanen 2004). The modeling techniques which are used are often similar, although in forecasting applications there is the opportunity to improve the model outputs by making use of observations up to the time of the forecast; a process which is called

Table 1.1 Some examples of forecast requirements for spatial scale and lead-time for a range of hydrometeorological forecasting applications (where this is technically feasible)

Application	Spatial scale	Lead-time
Drought Early Warning	Typically regional, national or continental	Varies widely depending on the application, with types of drought including hydrological, groundwater, soil moisture and socio-economic, but typically from days ahead to seasonal, and possibly longer for severe droughts (see Chapter 8)
Ecosystem Forecasting	Field, catchment or lake basin; also for coastal waters	A wide range of timescales, varying from hours to days ahead for pollution incidents, days to months ahead for Harmful Algal Blooms, and longer term for ecosystem impacts (see Chapter 10)
Famine Early Warning	Regional, national or continental	Ideally seasonal, with information available before the start of the main crop growing season(s) (see Chapter 8)
Flood Warning	Subcatchment, catchment or regional	Can vary from a few minutes for flash flooding in canyons, through to hours or days ahead for lowland rivers, the evacuation of people from towns or cities, reservoir releases and emergency response planning. Also, longer term for major river basins and flood risk management (see Chapter 7)
Hydropower Operations	Catchment or regional	Hourly to daily for production scheduling; daily to seasonal or longer for water resources management; longer term for operating large reservoirs and multi-reservoir systems and investment planning (see Chapters 5, 9 and 11)
Irrigation Scheduling	Field to catchment to regional	Hours to days ahead for water allocation; intraseasonal for operational decisions (e.g. fertilization, pest control), seasonal for planting/harvesting decisions; longer range for investment decisions (see Chapters 5 and 8)
Navigation	River reaches, lakes and reservoirs	Hours to days ahead for river traffic control and navigation warnings, including (as appropriate) estimates for water levels, flow velocities, wave heights, ice formation, ice break up and other hazards (see Chapters 4 and 7)
Pollution Incidents	Subcatchment, catchment or lake basin	From minutes to hours or days ahead for chemical, biological, radiation etc. incidents, through to longer term for general water quality and ecological applications (see Chapter 10)
Water Resources	Catchment or regional	Typically from hours to days ahead for operational management, through to weeks, years or decades ahead for river basin management, integrated water resources management, and climate change impact assessments (see Chapter 7 and 11)
Water Supply	Catchment or regional	Varies from hours to days ahead for tactical decision making regarding pumping, treatment etc., to days or months ahead for operational planning, and years ahead for investment decisions (see Chapters 5 and 9)

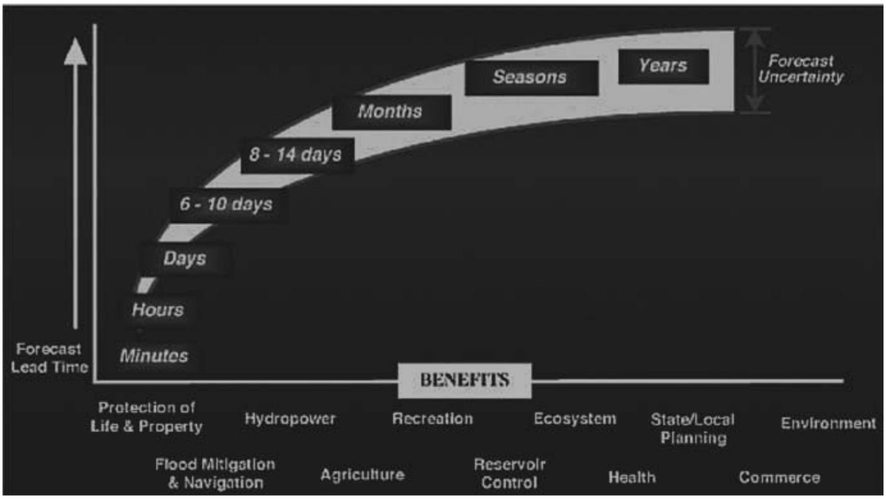

Fig. 1.1 Seamless probabilistic forecasts for all lead times (National Weather Service, Seo and Demargne 2008)

real time updating or data assimilation. Also, in forecasting applications (particularly for short lead times), models are often structured to make best use of the available real-time data, rather than around subcatchment features, such as river confluences.

A hydrometeorological forecasting system typically makes use of monitoring equipment, meteorological and hydrological forecasting models, and tools for post-processing forecasts into useful products. Demand forecasts may also be required for water supply, irrigation and hydropower operations and longer term planning. Recent decades have seen a gradual transition towards more automated, and more computationally-intensive approaches, although simpler or informal techniques still have a valuable role to play where budgets are limited, the risk is low, or as a back-up to more complex systems. Some examples include the use of informal techniques for flood warning (e.g. Parker 2003), community-based flood warning systems, and the expertise of farmers and pastoralists in recognizing the onset of drought.

The range of technologies available has also improved over the years, and developments include the increasing use of weather radar and satellite-based observations, the introduction of multimedia warning dissemination systems (e.g. for flood warning applications), and the widespread use of the internet for dissemination of forecasts. Geographic Information Systems (GIS) are also increasingly used for providing a spatial interpretation of forecasts. One notable example of the use of new approaches to the dissemination of forecasts is the international RANET initiative (Radio and Internet for the Communication of Hydro-Meteorological Information for Rural Development). The project uses a combination of satellite broadcasting, internet and mobile phone technologies to disseminate meteorological information to the public and between national meteorological services and other organizations in Africa, Asia, and elsewhere (http://www.ranetproject.net/). Scientific understanding of regional and global scale phenomena such as the El Niño-Southern Oscillation (ENSO) has also improved, making longer range seasonal forecasting a more realistic proposition in some locations (see Box 1.1). The modeling of climate change, and potential impacts, has also progressed significantly in recent years.

Table 1.2 summarises some significant milestones in the history of the development of hydrometeorological forecasting techniques, and many of these methods are discussed in later sections and chapters. Note that, for convenience, hydrodynamic modeling is considered as an aspect of hydrological forecasting, although is of course a major subject area in its own right.

Table 1.2 Some significant milestones in the development of hydrometeorological forecasting techniques

Period	General area	Description
1850–1900	Monitoring	First telegraphy of river levels and meteorological observations
	Meteorology	Launch of a Public Weather Service (US Army Signal Corps/Met Office)
	Hydrology	Rational method for runoff estimation (Mulvaney)
	Hydrology	St Venant hydrodynamic equations (St Venant)
1900–1929	Meteorology	Principles of Numerical Weather Prediction (NWP) (Bjerknes)
	Meteorology	Identification of the Southern Oscillation (Walker)
	Meteorology	Manual trials of the NWP approach (Richardson)
	Meteorology	Statistical seasonal (monsoon) prediction in India (Walker)
1930s	Hydrology	Unit hydrograph rainfall-runoff model (Sherman)
	Hydrology	Muskingum flow routing approach (Muskingum)
1940s	Meteorology	First trials of data assimilation in NWP (Panofsky)
	Hydrology	Penman evaporation equation (Penman)
	General	First general-purpose computer (ENIAC)
1950s	Monitoring	US NOAA WSR-57 weather radar network started
	Meteorology	First operational NWP models
	Meteorology	World Meteorological Organisation (WMO) established
1960s	Monitoring	First NASA TIROS satellite launched (polar orbiting/infrared)
	Monitoring	WMO World Weather Watch programme established
	Hydrology	Degree-day method for snowmelt (Martinec)
	Hydrology	Development of conceptual rainfall-runoff models
	Hydrology	Muskingum-Cunge flow routing approach (Cunge)
	Hydrology	Palmer Drought Severity Index (Palmer)
		Blueprint for physically-based distributed models (Freeze and Harlan)
	General	Kalman filter (Kalman)

Table 1.2 (continued)

Period	General area	Description
1970s	Monitoring	First geostationary earth observation satellite launched (SMS-A and B)
	Monitoring	European Space Agency (ESA) Meteosat I satellite launched
	Monitoring	NOAA/NASA GOES satellite programme started
	Hydrology	Development of time series models for hydrological forecasting
	Hydrology	Research on physically-based distributed rainfall-runoff models
	General	Introduction of email and internet protocols
1980s	Meteorology	First operational ocean-atmosphere coupled NWP models
	Hydrology	Ensemble Streamflow Prediction (ESP) method (Day)
1990s	Monitoring	TRMM space-borne precipitation radar launched
	Meteorology	First IPCC assessment report on climate change
	Meteorology	Four-dimensional variational data assimilation schemes (4D-Var)
	Meteorology	Operational ensemble meteorological forecasting (ECMWF, NCEP)
	Meteorology	Regional Climate Outlook Forums started (WMO)
	Hydrology	Hydrodynamic models publicly/commercially available
	Hydrology	Increasing sophistication of the land-atmosphere component in NWP
Since 2000	General	Multi-media warning dissemination systems available commercially
	General	Increasing use of coupled land-atmosphere simulation models
	Hydrology	Increasing use of probabilistic flood forecasting systems

The main reason for generating forecasts is to assist in decision-making, and the forecasting system is therefore often only one component in a wider operational framework. For example, Fig. 1.2 illustrates the role of prediction and early warning within the overall risk management and crisis management process for drought disasters, and a similar approach is often used for other types of natural hazards, such as floods. The key components in this process can include assessing the risk, typically through modeling, consultations, and reviews of historical events, preparing to deal with that risk, putting mitigation (risk-reduction) measures in place, issuing the early warning, responding to the disaster, and then a series of crisis management and recovery measures. For example, in famine early warning systems, hydrometeorological forecasts are often combined with other approaches, such as expert judgement on future trends, and observer and media reports on possible precursors of future problems, such as food shortages, and an increase in food prices.

Chapters 7, 8 and 10 provide further examples for warnings for floods, drought and pollution incidents, whilst Chapter 6 provides a general introduction to decision-making processes for emergencies, operational management and long term planning. Internationally, an increasing emphasis is also being placed on improving the way that disaster risk is prepared for and managed (e.g. UN/ISDR 2006a,

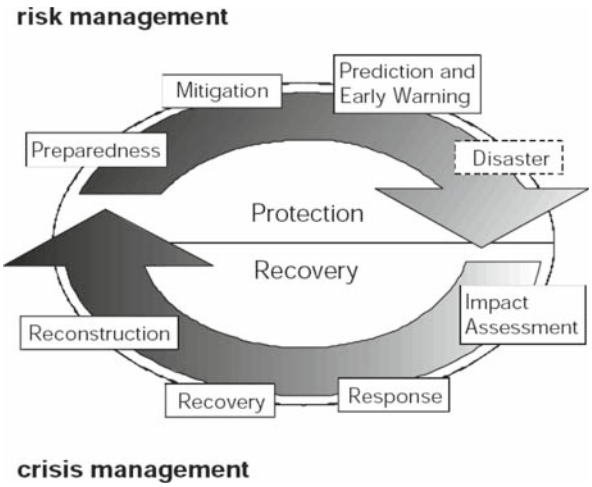

Fig. 1.2 The cycle of disaster management (National Drought Mitigation Center, University of Nebraska-Lincoln; Wilhite and Svoboda 2005)

2009), rather than on the ensuing emergency response and relief. This requires that all aspects of the process are given equal importance; not least the need to adopt a people-centred or community based approach (e.g. Emergency Management Australia 1999, Basher 2006). The point is also often made that the effectiveness of the response depends on a wide range of factors, including institutional capacity, social and economic factors and public awareness, so that what is a disaster for one country, causing many injuries and deaths, may only have economic consequences in another.

Risk management techniques are also widely used in decision making and Section 1.3 and later chapters discuss examples in hydropower operations, irrigation scheduling, water supply and a range of other applications, including examples which make use of probabilistic forecasts. For high risk (and high-value) applications, decision support systems are also increasingly used, combining Geographic Information System (GIS), optimization tools, and other computer-aided techniques for decision making.

1.2 Operational Forecasting

1.2.1 General Principles

As noted earlier, the main components in a hydrometeorological forecasting system typically include monitoring equipment, meteorological forecasting models, hydrological forecasting models, and possibly also demand forecasting models, and decision support tools. Table 1.3 illustrates some of the methods which are often used.

Table 1.3 Illustration of hydrometeorological forecasting tools and techniques

Component	Description
Monitoring	Techniques include raingauges, weather stations, weather radar, satellite observations, river gauges, and instrumentation for catchment conditions (e.g. soil moisture, snow cover); see Chapter 2
Meteorological forecasting	Techniques include nowcasting, Numerical Weather Prediction, and statistical methods, and may include statistical, weather matching or dynamic post-processing (downscaling) to the scales of hydrological interest; see Chapter 3
Hydrological forecasting	Techniques include statistical methods, water-balance methods, rainfall-runoff models, hydrological and hydrodynamic river flow routing models, and a range of approaches for individual features of a catchment, such as urban drainage networks, snowmelt, reservoirs, lake storage, water quality and ecosystems; see Chapter 4 and Chapters 7–11
Demand forecasting	Empirical, statistical and deterministic methods for estimating the water demands for water supply, irrigation and energy generation (particularly related to hydropower generation) and for industrial and other applications; see Chapter 5
Decision support	Techniques to assist users in making decisions, including graphical, tabulated and map-based forecast products, decision support systems, and threshold-based approaches; see Chapter 6

The extent to which each component is required depends on the application and, in particular, the forecast lead time which is required, and the flow range of interest. For example, in flood forecasting applications, in a large river catchment, sufficient lead time may be possible simply from using observations of flows further upstream in the catchment as inputs to the hydrological forecasting models; however, for a flash flood forecasting application, rainfall forecasts (often combined with a rainfall-runoff model) may provide the only feasible way of obtaining sufficient lead time for an effective emergency response. Demand forecasts may also be of little interest for flood forecasting, but are often a key input to procedures for the forecasting of low flows for drought, water resources management and other applications.

The availability of data is also an important consideration. This can mean that, for operational applications, at short lead times, there is a need for information to be relayed automatically by telemetry or manually by observers whereas, for longer lead times, and for model calibration, it may be sufficient to collect information from record sheets, charts or data loggers during site visits. Later chapters describe the lead time and data requirements and forecasting approaches for a range of applications.

In some countries, the national meteorological and hydrological services are part of the same organization, whereas in others they may be distinct organizations, each operating separate observation networks. A variety of other organizations may also collect real-time and off-line data, including agricultural research stations, reservoir operators, hydropower suppliers, water supply companies, canal operators, and others. Some of this data may potentially be available for use for hydrological forecasting applications, depending on local data sharing arrangements and policies.

The availability of data and forecasts also varies widely between organizations and countries. For example, in flood forecasting applications, a survey of 86 countries (World Meteorological Organisation 2006a) suggested that, where flood forecasting capability was non-existent or insufficient, this was often due to insufficient observational data, and issues relating to technical or institutional capacity.

For National Meteorological and Hydrological Services, the arrangements for data sharing are facilitated by the World Meteorological Organisation, which provides standards for the collection and exchange of data and forecast products, and for feeding data into the Global Telecommunication System (GTS). The GTS is a component of the World Weather Watch programme, and is "a dedicated network of telecommunication facilities and centres, using leased lines, satellite-based systems, the Internet, and data networks, that is implemented and operated by the National Meteorological and Hydrological Services of WMO Member countries all over the world" (World Meteorological Organisation 2006b). It is the main route for the exchange of data for use in weather forecasting models and includes information collected by the WMO Global Observing System from approximately 16 satellites, hundreds of ocean buoys, aircraft, ships and some 10,000 land-based weather and other meteorological stations (World Meteorological Organisation 2006b).

Other United Nations organisations such as the Food and Agriculture Organization (FAO) and the ISDR (International Strategy for Disaster Reduction) also play an important role in sharing expertise and information between countries and, for climate change assessments, the UNEP/WMO Intergovernmental Panel on Climate Change (IPCC) of course plays a key role. There are also many examples of international cooperation between hydrological services for transboundary river systems; the International Commission for the Protection of the Danube (http://www.icpdr.org), and the Mekong River Commission (http://www.mrcmekong.org/)). Table 1.4 summarises some other examples of international cooperation in research and operational activities in meteorology and hydrology which are discussed in later chapters.

The World Meteorological Organisation is also leading the World Hydrological Cycle Observing System (WHYCOS; http://www.whycos.org) initiative, which is aimed at improving basic observation activities in National Hydrological Services, strengthening international cooperation, and promoting free exchange of data in the field of hydrology (Rodda et al. 1993, World Meteorological Organisation 2005). Regional projects have been implemented in the Mediterranean area (MED-HYCOS), southern Africa (SADC-HYCOS), and a pilot study in western and central Africa (AOC-HYCOS), with many other projects planned or in progress. New hydrological stations typically consist of satellite Data Collection Platforms (DCPs) equipped to measure precipitation, air temperature, humidity, water levels (river, lake/reservoir, groundwater, as appropriate), wind speed and direction, and solar radiation. Water quality variables such as conductivity, turbidity and dissolved oxygen may also be monitored in some locations. Data values are typically transmitted between centres using the WMO's Global Telecommunication System (GTS).

Table 1.4 Examples of international cooperation in meteorology and hydrology

Abbreviation	Description
FRIEND	Flow Regimes from International Experimental and Network Data; a UNESCO-initiated programme of research into low flows, floods, variability among regimes, rainfall/runoff modeling, processes of streamflow generation, sediment transport, snow and glacier melt and climate and land-use impacts involving more than 100 countries http://www.unesco.org/water/ (1984-ongoing)
GEWEX	Global Energy and Water Cycle Experiment, a key component of the WMO World Climate Research Programme, whose goal is to reproduce and predict, by means of suitable models, the variations of the global hydrological regime, its impact on atmospheric and surface dynamics, and variations in regional hydrological processes and water resources and their response to changes in the environment, such as the increase in greenhouse gases http://www.gewex.org/gewex (1990-ongoing)
HEPEX	The Hydrologic Ensemble Prediction EXperiment (HEPEX) is an international effort that brings together hydrological and meteorological communities from around the globe to build a research project focused on advancing probabilistic hydrologic forecast techniques http://hydis8.eng.uci.edu/hepex/ (2004-ongoing)
PUB	The Predictions in Ungauged Basins (PUB) programme is an International Association of Hydrological Sciences (IAHS) initiative for the decade 2003–2012, aimed at uncertainty reduction in hydrological practice http://pub.iwmi.org/
WWRP	The WMO World Weather Research Programme, which advances society's ability to cope with high impact weather through research focused on improving the accuracy, lead time and utilization of weather prediction, and includes the THORPEX (1 day to 2 week ahead high impact forecasting; 2003–2013) and TIGGE (global grand ensemble forecast) components http://www.wmo.int/

The following sections provide an introduction to meteorological and hydrological forecasting techniques, and further details are provided in later chapters. A basic understanding of the hydrological cycle is assumed (and a brief introduction is provided in Section 4.2 of Chapter 4). For hydrological forecasting in particular, but also for meteorological forecasting, the methods which are used depend on the local weather and climate, and Fig. 1.3 shows typical rainfall regimes around the world, including high latitude regions which may experience snow cover for several months of each year. The precipitation which is observed can range from desert regions with little or no annual rainfall, through to areas such as Cherrapunji in India, and the island of Kaua'I in Hawaii, which experience average annual rainfalls which are often quoted to be in the range 11–12 m/year, and have reached more than 26 m/year at Cherrapunji (e.g. World Meteorological Organisation 1994). Extensive snow cover may also be experienced in mountain

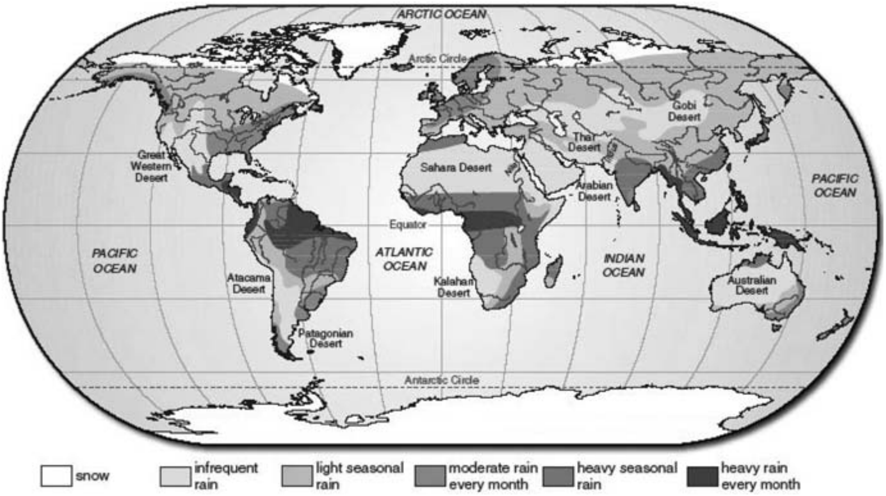

Fig. 1.3 Map showing world rainfall (© Open University, Halliday and Davey 2007) http://openlearn.open.ac.uk/mod/resource/view.php?id=293808&direct=1)

regions at mid-latitudes; for example, in the Western USA and Canada, the European Alps, the Andes, the Himalaya and, to a lesser extent, the high mountains of Africa.

1.2.2 Meteorological Forecasting

Meteorological forecasts are often classified as short-range for lead times up to 3 days ahead, and medium-range for 3–10 days ahead, whilst extended and long-range forecasts extend to seasonal and longer time periods (World Meteorological Organisation 1992). Forecasting techniques include nowcasting, Numerical Weather Prediction, and a range of statistical and hybrid techniques. These are described in Chapter 3 and are summarized in Table 1.5, together with two key approaches which can improve the usefulness of forecasts: post-processing and consensus forecasts.

Numerical Weather Prediction (NWP) models underpin many of these techniques and typically use global scale models to provide boundary conditions to regional and local models; for example, this approach is illustrated in Fig. 1.4, which shows the extent of the operational forecasting models operated by the Meteorological Office in the United Kingdom (the Met Office).

Data assimilation is also a key component in initializing model runs and, as indicated in the table, may include data from a wide range of observation systems. Also, since the 1990s, ensemble forecasting techniques have become standard practice in many meteorological services, and provide multiple realizations of future conditions, based on perturbations to the initial conditions of models to help to take

Table 1.5 Summary of key meteorological forecasting and post-processing techniques

Method	Typical maximum lead time	Basis of method
Nowcasting	0–6 h	Extrapolation of the motion of weather radar and/or satellite based rainfall intensity observations, possibly guided by the outputs from Numerical Weather Prediction models (in which case nowcasting can be regarded as a form of post-processing of NWP outputs). Also, manual or automated extrapolation of other parameters (e.g. fog, air temperature), and of the evolution of tropical storms (hurricanes, tropical cyclones, typhoons)
Numerical Weather Prediction (NWP)	0–10 days (deterministic), 0–15 days, seasonal (ensemble)	Three-dimensional modeling of the atmosphere on a horizontal grid and vertical layer basis, accounting for mass, momentum and energy transport and transfer at the land and (possibly) the ocean surfaces, and assimilating data from a wide range of land-based, oceanographic (buoys, boats etc.), atmospheric (aircraft, radiosonde) and satellite observation systems
Statistical methods	Weeks to seasonal	Multiple regression, canonical correlation analysis, and other techniques linking future weather to indicators or predictors such as sea surface temperatures, and indices for the El Niño-Southern Oscillation (ENSO) (and sometimes called Teleconnections)
Post-processing	As for Numerical Weather Prediction	Dynamic techniques, in which models are nested to provide finer resolution in locations of interest, and statistical techniques, which relate model outputs to ground conditions based on historical or recent observations. Also, analogue or weather matching techniques
Consensus forecasts or predictions	Typically intra-annual and seasonal	Forecasts agreed by experts in meteorology and other disciplines based on the outputs from a range of forecasting models and techniques. Examples include the WMO Regional Climate Outlook Forums active in several parts of the world, and the discussions which lead to the weekly updates of the US Drought Monitor (see Chapter 8)

account of uncertainty in current conditions, and possibly also the uncertainty in model parameters. Typically, 20 to 50 ensemble members are provided per time step. These outputs provide useful information to forecasters on uncertainty, and also open the way to wider use of probabilistic and risk-based decision making techniques. In some systems, performance statistics also show that the ensemble mean value improves upon the single-valued deterministic forecast, particularly at longer lead times.

In the short to medium-range weather forecasts issued to the public, the outputs from computer models are typically interpreted by operational forecasters

Fig. 1.4 Illustration of the spatial extent of the Met Office's UK, North Atlantic and European (NAE) and Global models (© Crown Copyright 2009, the Met Office)

who issue the forecast based on experience, comparisons with recent observations, synoptic charts, and the use of other tools to summarise atmospheric conditions. The outputs from models operated by other national meteorological services may also be taken into account, particularly for longer lead times, with the use of multi-model ensembles becoming increasingly widespread. Statistical and dynamic post processing techniques may also be applied to the raw model outputs, including tailor-made methods to produce forecast products to meet the needs of different users, including road-users, airports, farmers, businesses, industry and others.

For hydrological forecasting applications, the time series of model outputs are also of interest, particularly for flood warning and other short-term forecasting applications. Outputs can be obtained for a point location (e.g. a town centre) or spatially averaged (e.g. for a catchment) for input to hydrological models. Numerical Weather Prediction models can also provide a range of other outputs which can be useful in hydrological applications, including forecasts for evaporation, soil moisture, air temperature, and snow cover. More general information, such as that provided by consensus forecasts and statistical techniques, can also be used for sensitivity and 'what-if' studies.

Historically, one barrier to using forecasts in this way has been the coarse spatial resolution of model outputs, compared to typical hydrological scales of interest. For example, until recently, a typical grid-length for regional models was 10–20 km and, although nowcasting techniques can offer much higher resolutions (e.g. 1 km), this is typically only for lead times of up to a few hours at most for rainfall estimates.

However, due to improvements in computing power (typically using some of the world's fastest supercomputers), the resolutions of Numerical Weather Prediction models are now approaching those of nowcasting models for local (or limited) area, or regional, models. For example, models with grid scales of 1–5 km now becoming operational in some countries, typically at an hourly run interval (compared to 6 hourly or 12 hourly for global scale models). However, due to the additional computer time required, ensemble forecasts are still typically at a lower spatial resolution. The improvements in resolution have also contributed to improvements in forecast accuracy; for example, for the forecasts issued by the UK Met Office, 3-day forecasts are now as accurate as 1-day forecasts were 20 years ago (http://www.metoffice.gov.uk/science/). However, there are of course limitations on predictability from the non-linear, chaotic nature of the atmosphere. These arise since small disturbances from the land surface and atmosphere can grow rapidly and interact, which is often called the 'butterfly effect', and was first popularized by Lorenz (e.g. Lorenz 1993).

The development of seasonal and decadal forecasting techniques is also an area of active research. Approaches include statistical methods, and the operation of coupled atmospheric and ocean models out to lead times of several months to capture the influence of phenomena such as the El Niño-Southern Oscillation and other regional or global scale features (see Box 1.1). Approximately 10 national and international meteorological organisations are designated as World Meteorological Organisation Global Producing Centres (GPCs) of long-range forecasts, including the Bureau of Meteorology in Australia, the China Meteorological Administration/Beijing Climate Center, the European Centre for Medium-Range Weather Forecasts (ECMWF), the Japan Meteorological Agency/Tokyo Climate Center, and the UK Met Office. Similar techniques are also used for the General Circulation Models used in modeling the impacts of climate change for years to decades ahead.

Box 1.1 Regional and global scale features of the atmosphere

In many parts of the world there are distinct seasonal influences and large-scale features of the atmosphere which are in principle predictable, even if only to provide a general indication of the timing and location of events, and in probabilistic terms. Some key driving mechanisms include variations in solar radiation, atmospheric waves, heat and water transfer at the ocean boundary, and related factors, such as the strength and position of the jet stream at mid-latitudes, and blocking anticyclones. In particular, the timescales over which the oceans respond are slower than for the atmosphere, and the heat capacity larger, raising the possibility of forecasting atmospheric changes over longer timescales, if the links between changes in the atmosphere and oceans can be understood.

The investigation of these phenomena is a key area for research in meteorology, and also in the wider search for so-called 'teleconnections' which relate observations or forecasts in one part of the world to impacts in another. Some key mechanisms which have been identified as either primary or secondary driving factors (and which to some extent are all inter-related) include (e.g. Palmer and Hagedorn 2006, Troccoli et al. 2008):

- El Niño-Southern Oscillation – abnormal increases (beyond the usual seasonal variations) in sea surface temperatures (SST) in the eastern and central Pacific, over characteristic periods of 2–7 years, for durations typically of a few months or more, linked to variations in the surface and sub-surface circulations in the Pacific Ocean. El Niño episodes tend to alternate with cooling (La Niña) episodes and drive a global atmospheric pressure variation called the Southern Oscillation, leading to the widely used term El Niño-Southern Oscillation (ENSO). ENSO events in particular have a strong influence on sea level temperatures and pressures and tropical rainfall, and the northern hemisphere jet stream and the Madden Julian Oscillation, so the impacts can occur in many parts of the world (see later)
- Inter Tropical Convergence Zone (ITCZ) – the convergence zone between the trade winds in the northern and southern hemispheres, which results in an uplift of air and generation of heavy convective rainfall and thunderstorms around the equator. Over land, the north-south position follows a meandering path linked to the zenith of the sun, with widths of several hundred kilometres, typically reaching a latitude of about 10° north or south, but with effects extending as far as 45° north in parts of southeast Asia. This often leads to two wet seasons and two dry seasons near the equator, merging into single wet and dry seasons at the northern and southern limits
- Madden Julian Oscillation (MJO) – intraseasonal patterns of atmospheric circulation, and enhanced and suppressed tropical rainfall (Madden and Julian 1994), which progress eastwards from the Indian Ocean into the western Pacific Ocean, and to a lesser extent the Atlantic Ocean, variously described as having a timescale of approximately 30–60 or 40–50 days, but with strong variations from year to year. Areas affected include the western USA, the Pacific Northwest and southeast Asia, with impacts also on the Indian and Australian monsoons, and tropical cyclones, and the northern hemisphere jet stream, with the greatest impacts during weak La Niña years, and little activity during strong El Niño episodes
- Monsoon – linked to the seasonal variations in prevailing winds driven by temperature (and hence air pressure) differences between the oceans and land surfaces, resulting in increased rainfall during the period when winds are on-shore, and affecting many regions where large land masses

are adjacent to the ocean (e.g. in parts of west Africa and Central America, and southeast Asia). Most notable in the form of the Asian Monsoon, which typically lasts from June to September, and for which the countries affected include Bangladesh, India, Nepal, Pakistan and Sri Lanka

- North Atlantic Oscillation (NAO) – a mainly atmospheric phenomenon, although linked to ocean surface conditions, which appears as an oscillation which can persist for several years in the relative positions and strengths of the permanent high pressure region around the subtropical Atlantic (the Azores High) and the low pressure in Arctic regions (the Iceland Low). Affects the strength and tracks of storms across the Atlantic and into Europe (particularly in winter), with influences on air temperatures and rainfall from a region extending from southern Europe and North Africa (in weak NAO years) to central and northern Europe (in strong NAO years), and to a lesser extent the eastern USA and Canada (e.g. Hurrell et al. 2003)

Other longer term signals have also been identified, such as the Pacific Decadal Oscillation, which is an oscillation in surface temperatures over 2–3 decades in the mid-latitudes of the Pacific Ocean (Mantua et al. 1997). The influence of the El Niño-Southern Oscillation is perhaps the most active area for research, and the impacts can be widespread, particularly in equatorial and tropical regions surrounding the Pacific Ocean, but also in other locations, as illustrated in Fig. 1.5 for both El Niño and La Niña events. For example, the 1982–83 and 1997–98 El Niño events affected countries in Africa, Asia, the United States and South America (e.g. Hoerling and Kumar 2003, NDMC 2009).

As noted in NDMC (2009) ‘In general, when El Niño conditions develop in the eastern Pacific, the first visible impacts include an increase in precipitation in the eastern Pacific, including parts of South America, and a decrease in precipitation for western Pacific locations such as Australia, Indonesia, Southeast Asia, and the Philippines. As the El Niño continues, other impacts include a significant decrease in tropical storm activity in the Atlantic Ocean and a corresponding drought in the Caribbean and Central America. Tropical storm activity increases in the eastern Pacific. Anomalously wet conditions are common across the southern United States and eastern Africa. Severe droughts can also occur in southern Africa and in northeastern Brazil’.

Publicly available bulletins on the progression of El Niño events include the WMO El Niño/La Niña Updates issued through a collaborative effort between the WMO and the International Research Institute for Climate and Society (IRI) (http://www.wmo.ch/) and the weekly and monthly updates issued by the NOAA/National Weather Service Climate Prediction Center in the USA (http://www.cpc.noaa.gov/).

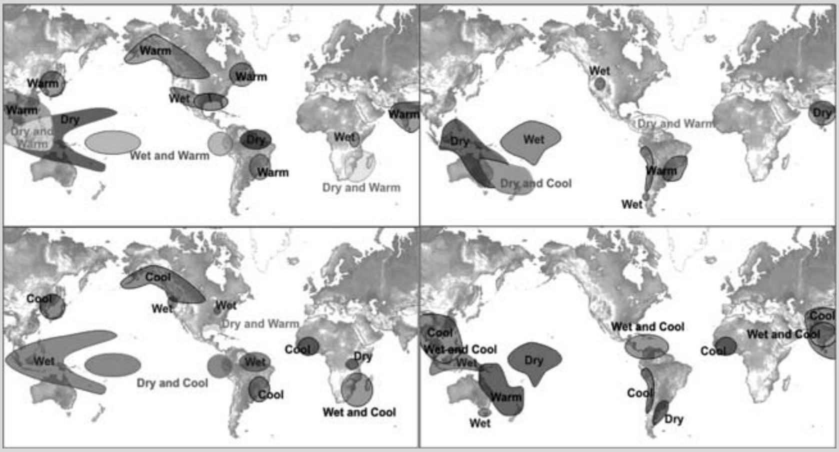

Fig. 1.5 The regions where the greatest impacts occur due to the shift in the jet stream as a result of ENSO. Top row: El Niño effect during December–February (*left*) and June–August (*right*), lower row: La Niña effect during December–February (*left*) and June–August (*right*) (Source: NOAA, http://www.riverwatch.noaa.gov/jetstream/tropics/enso_impacts.htm)

Seasonal forecasting techniques include the use of coupled ocean-atmosphere Numerical Weather Prediction models, and statistical and spectral techniques linking impacts to indicators and predictors such as sea surface temperatures, and latitudinal differences in sea surface air-pressure (e.g. the Southern Oscillation Index SOI and North Atlantic Oscillation Index). For example, sea surface temperatures can be forecast using ocean models, and observed by satellite and ocean buoys, and there are approximately 70 deep ocean buoys in the international Tropical Atmosphere Ocean (TAO/TRITON) array in the equatorial Pacific Ocean (http://www.pmel.noaa.gov/tao/). Some further description of seasonal forecasting techniques is presented in Chapters 3 (in general terms), 7 (for floods) and 8 (for droughts).

1.2.3 Hydrological Forecasting

Hydrological forecasts can be generated using a range of techniques; however, a typical approach is to use observation or forecasts of rainfall as inputs to conceptual, data-driven or distributed (grid-based) rainfall-runoff (hydrologic) models. These may in turn provide inputs to hydrological or hydrodynamic flow routing models, which translate flow through the river network. Simpler water balance techniques are also sometimes used, and demand forecasts may also need to be considered in some applications.

Short-term hydrological forecasts are generally considered to extend 2 days from issue of the forecast, whilst medium-term forecasts extend from 2 to 10 days, long-term forecasts beyond 10 days, and seasonal forecasts for several months (World Meteorological Organisation 2008). Models may be operated at a local, catchment or regional scale, and sub-models may also be included for a range of influences, including urban drainage, reservoir control, water quality issues, and other factors. As for meteorological models, the availability of real-time data means that, at least at short to medium lead times, the outputs from hydrological forecasting models can be updated to help to account for the differences between observed and forecast values; a process which is often called real-time updating or data assimilation.

In addition to rainfall, a number of other meteorological variables may also be of use as inputs to hydrological forecasting procedures, and Table 1.6 shows some examples. Note that rainfall, snow, hail, drizzle etc. are often referred to collectively as precipitation, and that evaporation losses occur directly from open water, plant interception or soil surfaces, whilst transpiration arises from plants drawing up water from deeper soil layers. The combination of the evaporation and transpiration terms is often called evapotranspiration (although some definitions exclude the open water component). The use of coastal forecasts of surge and tidal levels can be relevant in some hydrological forecasting applications, such as in providing a downstream boundary condition for a river hydrodynamic model.

Meteorological variations can also affect the demand for water, both directly, by increasing the requirements for water consumption (e.g. for drinking water, or irrigation), and indirectly; for example, by increasing the demand for sources of electricity which rely on water either for power generation (e.g. hydropower plants) or for cooling (e.g. thermoelectric plants). Some typical demand forecasting techniques include multiple regression approaches, data-driven methods, such as artificial neural networks, process-based models (e.g. crop simulation models), and micro-component approaches, in which the total demand is estimated from the sum of individual types of use (e.g. drinking water, bathing water). Methods can

Table 1.6 Some examples of the use of meteorological inputs in hydrological forecasting applications

Parameter	Typical model components
Precipitation	Surface runoff, reservoir and lake levels, urban drainage, groundwater levels
Snow	Snow cover, snow depth, snow density
Air temperature	Snowmelt, evaporation, transpiration, evapotranspiration
Humidity	Evapotranspiration, snowmelt
Radiation	Evapotranspiration, snowmelt, ice break-up
Wind speed	Wave heights on lakes and reservoirs (and surge on large water bodies, and in estuaries), evapotranspiration, snowmelt
Wind direction	Wave directions on lakes and reservoirs and in estuaries

be very specific to the particular application, and Chapter 5 describes a range of approaches for water supply, irrigation and energy generating applications.

For short- to medium-term forecasting, National Hydrological Services and other forecasting centers typically operate models within a computer forecasting system. Systems of this type usually have the facility to receive real-time data and forecasts from a range of sources (e.g. raingauges, river gauges, weather radar, Quantitative Precipitation Forecasts), to operate the models, and then to post-process the outputs into map-based, graphical and other formats for a variety of users. Models are typically operated at least once per day, and more frequently during flood events. The system may be designed primarily for use during particular types of hydrological event (e.g. flooding), or cover a range of applications in flooding, droughts, water resources management, and other areas. For example, Box 1.2 describes the operational forecasting system used by the California-Nevada River Forecasting Center, which is part of NOAA's National Weather Service in the USA.

For longer term forecasting, the reduced pressure on lead times means that models can sometimes be operated off-line, although there are often good reasons for using a more formalized system, such as improvements to data quality control and record keeping, and operational efficiencies. Some typical modeling approaches at these lead times include supply-demand models, which can represent the main sources and demands for water to a high level of detail, simplified integrated catchment models, and distributed models, operating on a gridded basis. For example, supply-demand models are widely used in river basin management, hydropower and other applications, and often include a linear or dynamic programming component to help to optimize operating strategies.

Also, an increasing trend in forecasting applications is to develop models which consider all key meteorological inputs, flow pathways and artificial influences on flows from the headwaters to the coast. Some research examples include the 'clouds-to-catchment-to-coast' concept in the Flood Risk from Extreme Events (FREE) programme in the UK (http://www.free-uk.org/) and the 'Sky to the Summit to the Sea' approach in the Coastal and Inland Flooding Observation and Warning Project (CI-FLOW) in the USA (http://www.nssl. noaa.gov/).

The Source-Pathway-Receptor approach is also widely used in environmental applications to consider the impacts of flooding, pollution and other factors on people and the environment, and can be applied at a local level (e.g. for a point source of pollution affecting an aquifer) through to a catchment or regional scale. For example, Chapter 6 illustrates this approach for a flood risk management application. For longer term forecasts and prediction, and particularly for climate change impact assessments, process-based techniques are increasingly used and – as described in Chapter 11 – in addition to the water and energy fluxes between the land, atmosphere and oceans, may also consider additional factors, such as the carbon cycle, and the role of atmospheric chemistry in affecting meteorological and hydrological conditions. Some other factors which may be considered include urban drainage and pollution, changes in land use, vegetation, and ecosystems, and the effects of forest fires and volcanoes.

Box 1.2 California-Nevada River Forecast Center (CNRFC)

The California-Nevada River Forecast Center (CNRFC) is one of 13 River Forecast Centers (Fig. 1.6) in NOAA's US National Weather Service (NWS), whose main functions are (http://www.cnrfc.noaa.gov/):

- Continuous hydrometeorological data assimilation, river basin modelling, and hydrologic forecast preparation
- Technical support and interaction with supported and supporting NWS offices
- Technical support and interaction with outside water management agencies and users
- Applied research, development, and technological implementation to facilitate and support the above functions.

The head office is in Sacramento in California, and responsibilities include providing forecasts for flood control, reservoir inflows, water supply, irrigation, recreation, spring snowmelt, and flash flooding. Forecasts are provided for a range of timescales, from short-term deterministic forecasts through to long-term probabilistic forecasts for the weeks and months ahead.

Fig. 1.6 National Weather Service River Forecast Centers in the United States (http://www.weather.gov/ahps/rfc/rfc.php)