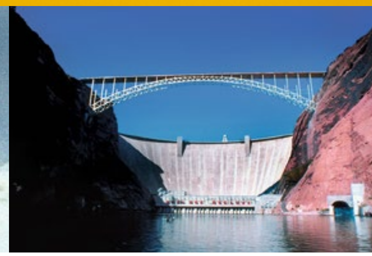
Kevin Sene





Hydro-meteorology

Forecasting and Applications

Second Edition

Springer

Hydrometeorology

Kevin Sene

Hydrometeorology

Forecasting and Applications

Second Edition

Springer

Kevin Sene
United Kingdom

ISBN 978-3-319-23545-5 ISBN 978-3-319-23546-2 (eBook)
DOI 10.1007/978-3-319-23546-2

Library of Congress Control Number: 2015949821

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Preface to the Second Edition

In addition to the many practical applications, one of the most interesting aspects of hydrometeorology is how quickly techniques change.

Since publication of the first edition, some of the main steps forward have been in meteorology. In particular, high-resolution convection-permitting numerical models are now used operationally by several meteorological services, improving the ability to forecast convective storms. With typical horizontal scales of 1–2 km, the outputs are of interest in a wide range of hydrological applications. Data assimilation techniques have also been developed further to make more use of higher-resolution observations such as those provided by weather radars and wind profilers.

Regarding weather radar, the most significant development has been the dual-polarisation upgrades that are underway or have been completed in several countries. Compared to Doppler techniques, this approach improves the ability to distinguish between types of precipitation together with several other advantages, with corresponding improvements in the accuracy of precipitation estimates. The Core Observatory satellite for the international Global Precipitation Measurement mission was also launched in 2014 and offers the potential for a step-change in the accuracy and global coverage of satellite precipitation estimates.

At catchment scale, the reliability of water quality sensors continues to improve allowing continuous monitoring of an ever-widening range of contaminants. Some typical applications include real-time water quality and ecosystem forecasting systems and investigations into the sources of diffuse pollution. More generally probabilistic forecasting techniques are being used in an increasing number of water resources, flood and other applications. For example, seasonal flow forecasts are necessarily probabilistic in nature and are increasingly used in reservoir management and agricultural operations.

However, a forecast on its own is of little value, and developments in cell phone and smartphone technologies continue to open up new approaches to issuing alerts and guidance to end users. Web-based information services and multimedia dissemination systems are now well-established, and many national services now use social media to keep people informed during emergencies. Taken together these developments allow forecasts and warnings to be issued more effectively than was possible even just a few years ago.

This revised version of the book provides an introduction to these various topics as well as to other longer-established techniques. It follows the same structure as before with an initial section that focusses on observation and forecasting techniques and how forecasts contribute to decision-making. A second section then discusses a range of practical applications in the areas of floods, droughts, flow control, environmental impacts and water resources. Many chapters have been significantly revised, and the previous chapters on monitoring and floods have been split into two parts, covering meteorological and catchment monitoring techniques and riverine and flash floods. This has allowed more detail to be provided on topics such as weather radar, debris flows and surface water flooding.

As before the text is generally at an introductory level, and each chapter contains extensive lists of references for further reading on the more technical aspects and mathematical background. This includes references to a number of excellent guidelines that have been published since the first edition; for example, as part of the WMO/GWP Associated Programme on Flood Management. Several new 'text-boxes' and tables are included which in some cases are updated versions of descriptions which first appeared in a book on flash floods: an area in which there is perhaps the greatest need for collaboration between meteorologists and hydrologists.

United Kingdom Kevin Sene

Preface to the First Edition

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 to provide 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 predefined 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 (e.g. 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.

United Kingdom Kevin Sene

Acknowledgments

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 in the United Kingdom. There, I had the opportunity to work on a wide range of research and consultancy projects, with much of this work overseas. Subsequently, as a part of a large engineering consultancy, my focus turned to real-time applications, including areas such as probabilistic forecasting and flood warning.

As a part of project and research work, discussions with colleagues have been invaluable and there are far too many people to mention individually. 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.

In writing this book, a number of people have helped with providing permission to use figures and/or to include a discussion of their projects or systems. Most chapters include short case studies in the form of text boxes, and the following people have helped by providing comments on the text and permission to use the associated figures (Box numbers are shown in brackets): K. Beven (3.1), G. Charchun (6.2), M. Cranston (8.1, 9.3), A. Gobena and G. West (13.1), A. Green (2.3), R. Hartman (1.3, 11.1), G. Huffman and R. Gran (2.2), C. McPhail (12.3), G. Munoz (6.1), P. Schlatter (2.4), E. Sprokkereef (8.2), J. van Steenwijk and G. Stroomberg (12.2), N. Tuteja (13.2) and B. Vincendon (4.2).

As in the first edition I would also like to thank Clive Pierce for providing a significant re-write (and subsequent update) of Box 4.1, and Frank Weber for the description on which Box 13.1 is based. Reiterating thanks from the first edition, other people who allowed figures to be used (with the figure numbers shown in brackets) include B. Davey and M. Keeling (1.4), K. Stewart (3.8, 3.9) and M. Brown (Table 10.5). Heiki Walk also provided the text on short-term load forecasting in Box 6.2. Finally, from Springer, I am grateful to Robert Doe and Naomi Portnoy for their help and advice throughout the process of writing and publishing the book.

Where figures are from external sources, such as publications, conference presentations and websites, this is acknowledged in the figure captions. However, for completeness, the following list summarises the sources of the figures which are included:

BC Hydro (Box 6.2, 13.1; Figs. 6.7, 6.8, 13.3, 13.4, 13.5)
Bureau of Meteorology (Box 13.2, Figs. 4.5, 13.6, 13.7)
Cabinet Office (Fig. 4.3)
Defra (Figs. 9.8 (*part*), 9.9)
Environment Agency (Figs. 7.1, 11.8)
European Centre for Medium-Range Weather Forecasts (Figs. 4.1, 4.7, 4.8, 4.12)
Food and Agriculture Organization (Box 6.1, Figs. 6.2, 6.4, 6.5)
International Commission for the Hydrology of the Rhine Basin (Fig. 12.3)
Joint Research Center (Fig. 10.3)
Lancaster Environment Centre (Box 3.1; Figs. 3.5, 12.4)
Met Office (Box 2.3, 4.1; Figs. 1.6, 1.14, 2.5, 2.6, 2.7, 3.6, 4.2, 4.3, 4.5, 4.6, 9.6)
Météo France (Box 4.2; Figs. 4.9, 4.10, 4.11)
NASA (Box 2.2)
National Drought Mitigation Center (Figs. 1.2, 10.1)
National Oceanography Centre (Figs. 5.6, 8.12)
NOAA/Great Lakes Environmental Research Laboratory (Figs. 3.4, 11.4, 12.5, 12.6, 12.7; Table 12.3)
NOAA/National Weather Service (Box 1.3, 2.4, 11.1; Figs. 1.3, 1.5, 1.7, 1.8, 1.10, 1.11, 1.12, 1.13, 2.8, 5.11, 7.3, 7.6, 9.1, 9.7, 11.5, 11.6)
Office of Science and Technology (Fig. 8.5)
Open University (Fig. 1.4)
Rijkswaterstaat (Box 8.2, 12.2; Figs. 8.7, 8.8, 11.7, 12.2, 12.3)
Scottish Environment Protection Agency (Box 8.1, 9.3, 12.3; Figs. 8.4, 9.10, 9.11, 12.8)
Springer (Figs. 2.3, 3.2, 3.3 (*part*), 4.4, 5.1, 5.3, 5.10, 7.2, 8.3, 8.6, 8.9, 8.13, 9.3, 9.5, 9.8 (*part*), 9.14 (*part*), 11.1, 11.2, 13.2)
Tennessee Valley Authority (Fig. 6.6)
Urban Drainage and Flood Control District (Figs. 3.8, 3.9)
U.S. Army Corps of Engineers (Fig. 9.13)
U.S. Environmental Protection Agency (Fig. 11.9)
U.S. Geological Survey (Figs. 3.3 (*part*), 5.4, 6.1, 9.12)
U.S. National Parks (Fig. 9.14 (*part*))
World Meteorological Organisation (Figs. 1.7, 1.9, 2.1, 2.2, 3.7, 5.2, 7.3, 8.1, 9.2, 10.2, 11.3, 13.8)

Contents

Chapter 1
Introduction

Abstract Hydrometeorological forecasts are used in a wide range of applications such as early warning systems, reservoir operations, pollution control and river basin management. Typically meteorological observations and forecasts are used as inputs to hydrological models, whose outputs are then processed into a range of products tailored to operational needs. Increasingly this includes estimates for the uncertainty in forecasts, based on probabilistic techniques. This chapter presents a general introduction to these topics including developing areas such as seasonal forecasting and risk-based approaches to decision-making.

Keywords Hydrometeorology • Meteorology • Hydrology • Hydrologic • Demand Forecast • Lead time • Decision-support • Risk based • Probabilistic • Ensemble

1.1 Forecasting Applications

1.1.1 Basic Concepts

The main purpose of a hydrological forecasting system is usually to provide estimates for future conditions based on observations and meteorological forecasts. Some typical applications include providing warnings of impending floods, forecasting the onset and progression of droughts and assisting with water supply, irrigation and hydropower operations. Longer-term uses include river basin planning and climate change impact assessments.

For example, a meteorological service might issue a forecast that 150 mm of rainfall is expected in the next 24 hours or that there is a 45 % chance that rainfall will be below normal in the next 3 months. A hydrological service would then interpret this information in terms of the likely impacts such as a threat of flooding in the next few days or of low reservoir levels in coming months.

One key consideration is the lead time provided, which the World Meteorological Organisation (WMO 2012a) defines as the 'Interval of time between the issuing of a forecast (warning) and the expected occurrence of the forecast event'. Figure 1.1 shows a simple example for the case of an isolated storm leading to a rapid rise in river levels. Here the flood risk is assessed by comparing the forecast levels with a predefined flood alert value which, in this

K. Sene, *Hydrometeorology*, DOI 10.1007/978-3-319-23546-2_1

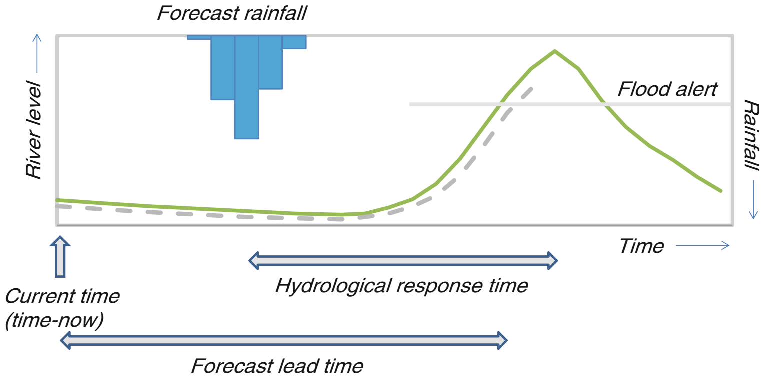


Fig. 1.1 Example of the lead time available from a hydrological model using rainfall forecasts as inputs for a simple flash flood scenario. The river-level forecast – issued at 'time now' – is shown as a dotted line together with the river levels that were subsequently observed; in reality these would of course not be available at the time of the forecast

case, is anticipated to be exceeded. However, in practice many factors need to be considered even for this simple situation; for example, how accurate was the rainfall forecast, does the hydrological model consistently underestimate levels and would organisational procedures allow a warning to be issued on the basis of a forecast alone? These more general issues of forecast interpretation and forecast verification are discussed in later sections and chapters.

In practice early warnings are typically escalated as parameters such as river levels rise or water quality deteriorates. Warning codes and messages vary widely between organisations although three- or four-stage alerts are typical in flood and tropical cyclone warning systems, for example, using terms such as alert, advisory, watch and warning.

Rapidly developing situations such as flash floods are some of the most demanding forecasting problems due to the limited time available to receive observations, run models and issue warnings. In contrast, for some reservoir and river basin management applications, projections are required for months to years ahead. Although the boundaries are not clear-cut, some typical lead-time requirements for the applications discussed in later chapters include:

- Minutes to weeks ahead – flood warning, hydropower scheduling, irrigation scheduling, water supply operations, pollution control and predictive control for urban drainage systems
- Weeks to months ahead – drought forecasting, planting/harvesting of crops and annual snowmelt forecasts
- Months to years ahead – river basin planning, climate change impact assessments and the operation of reservoir systems with large over-year storage

The terms seasonal and intra-annual are sometimes used to describe within-year variations and interannual for longer-term variations.

Table 1.1 provides more background information on typical lead-time requirements together with an indication of typical spatial scales. Here a sub-catchment is that part of the catchment above the point at which a forecast is required, which is normally called a forecast or forecasting point. However, as discussed in later chapters, due to technical limitations it is not always feasible to meet these requirements. Note that some alternative names for a catchment include river basin and watershed.

1.1.2 Technical Aspects

Table 1.2 illustrates the various components which are typically included in an operational flow forecasting system. However, the extent to which these are required depends on the application and, in particular, on the lead times, spatial scales and flow ranges of interest. For example, in a large river catchment, sufficient advance warning of flooding may be possible simply from using observations of river flows from a gauge further upstream; however, for a small upland catchment the only feasible way to obtain indications of flooding potential in time to act might be to rely on rainfall forecasts. Similarly, whilst demand forecasts are often a key input for drought and water resources applications, they are often less relevant to flood forecasting applications.

Flow forecasting systems are normally operated by national hydrological services and sometimes other organisations such as reservoir operators, river basin authorities and water supply utilities. In some countries the national meteorological and hydrological services are combined, although one survey (WMO 2008a) suggested that this was the case in less than half of the 139 countries considered. However, a common alternative is to establish a joint operations or forecasting centre at a national level to facilitate cooperation between meteorologists, hydrologists and disaster risk managers.

As indicated in Table 1.2, river and rainfall observations are usually some of the key inputs to a forecasting system. In many countries the first routine observations began in the late nineteenth or early twentieth century, and values would typically be recorded manually by paid or volunteer observers at set times each day. The record sheets would then be posted to (or collected by) regional or national centres at regular intervals for further processing; indeed, many hydrological services have archives of such records dating back several decades. During emergencies values would be relayed more frequently by phone or radio. This general approach is still widely used nowadays either as a backup to automated approaches or as the primary approach where budgets do not allow more automated systems.

The first public weather forecasting services began in the nineteenth century as did remote transmission of data, using telegraphy systems. River flow forecasting services were first introduced early in the twentieth century, and one of the first

Table 1.1 Some examples of typical user requirements for a range of forecasting applications, subject to technical feasibility

Application	Typical spatial scale	Typical lead-time requirements
Drought early warning	Water supply scheme, regional, national or continental	Varies widely depending on the application, with types of drought including meteorological, hydrological, groundwater, soil moisture and socioeconomic, ranging from hours to days ahead for real-time operation to seasonal and longer timescales for severe droughts (see Chap. 10)
Ecosystem forecasting	Field, lake, reservoir, catchment or lake basin; coastal waters	A wide range of timescales varying from hours to days ahead for pollution incidents, days to weeks ahead for harmful algal blooms and longer term for ecosystem impacts (see Chap. 12)
Famine early warning	Regional, national or continental	Ideally seasonal or better, with information available before the start of the main crop growing season(s) (see Chap. 10)
Flood warning	Sub-catchment, catchment or regional	Can vary from a few minutes to hours ahead for flash floods and related phenomena such as debris flows, urban flooding, dam breaks and ice jam floods, through to hours or days ahead for low-lying areas in large river catchments (see Chaps. 8 and 9)
Hydropower operations	Hydropower scheme, catchment or regional	Minutes to hourly or daily for production scheduling; daily to seasonal or longer for water resources management; longer term for investment planning (see Chaps. 6, 11 and 13)
Irrigation scheduling	Irrigation scheme, catchment or regional	Hours to days ahead for crop water allocation; intra-seasonal for operational decisions (e.g. fertilisation, pest control); seasonal for planting/harvesting decisions; longer range for investment decisions (see Chaps. 6 and 10)
Navigation	River reaches, canals, lakes or reservoirs	Hours to days or months 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 Chap. 8)
Pollution Incidents	Sub-catchment, river reach, 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 Chap. 12)
Water resources	Sub-catchment, catchment, regional or continental	From hours to days ahead for operational management to weeks, years or decades ahead for river basin management, integrated water resources management and climate change impact assessments (see Chaps. 10 and 13)
Water supply	Water supply scheme, sub-catchment, catchment or regional	Varies from minutes or 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 Chaps. 6, 10, 11 and 13)

Table 1.2 Illustration of some typical technical aspects of a flow forecasting service

Component	Description
Meteorological observations	Observation techniques include raingauges, weather stations, weather radar, satellite precipitation estimates and multisensor products; see Chap. 2
Catchment monitoring	Monitoring techniques include river gauges, reservoir gauges, tide gauges, soil moisture sensors, snow pillows, water quality sensors and satellite-based observations; see Chap. 3
Meteorological forecasting	Forecasting techniques include nowcasting, numerical weather prediction and statistical methods, plus statistical, weather-matching and dynamic post-processing techniques; see Chap. 4
Hydrological forecasting	Forecasting techniques include statistical methods, water-balance approaches, 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 Chaps. 5, 8, 9, 10, 11, 12 and 13
Demand forecasting	Forecasting techniques include empirical, statistical and microcomponent-based approaches for estimating withdrawals (abstractions) for water supply, irrigation, hydropower and other applications; see Chap. 6
Forecast interpretation	Approaches include risk-based and threshold-based techniques and decision-support systems, including the use of probabilistic forecasts and software tools for post-processing outputs into the required formats; see Chaps. 7, 8, 9, 10, 11, 12 and 13

rainfall-runoff modelling techniques (the unit hydrograph) was developed in the 1930s although is rarely used in forecasting applications nowadays. The first general-purpose computer came into use in the 1940s and some other significant developments since then – in general terms – include:

- Weather radar – the introduction of ground-based radar stations in the 1950s for remote monitoring of rainfall, typically with upgrades to Doppler systems in the 1990s and dual-polarisation capability since about 2010 (see Chap. 2)
- Satellite observations – the launch of the first earth-observing satellites in the 1960s, since then used for an ever-increasing range of applications, including the launch of the first spaceborne precipitation radar in the 1990s (see Chap. 2)
- Telecommunications – development of satellite, broadband and cell phone-based data transmission systems starting in the 1970s (for geostationary satellites) and accelerating in recent years, as alternatives to existing radio or landline-based systems (see Chap. 3)
- Numerical Weather Prediction – the introduction of numerical weather forecasting models into operational use in the 1950s with routine use of ensemble techniques starting in the late 1980s/early 1990s (see Chap. 4)

Another significant development has been the rapid adoption of cell phone, smartphone and web-based technologies, and this has revolutionised the options available for issuing warnings and forecasts, including in some of the poorest parts of the world, albeit with some caveats about reliability which are discussed in later chapters.

A modern-day forecasting system normally makes use of many sources of data and types of model and provides information that underpins a wide range of forecasting products and services. Hydrological forecasting centres are usually staffed year round with additional staff on call during emergencies during which time operations are typically around the clock (24/7). During normal times, training, system development and other activities are usually a full-time occupation; for example, in a flood forecasting service, WMO (2011a) notes that some typical staff duties include operational activities (e.g. making forecasts), modelling (model calibration), hydrometry (e.g. data collection, transmission, management and quality control) and informatics (e.g. equipment and system operation, providing appropriate output formats).

However, despite these advances, it is important to note that there remain wide variations in forecasting capability and, in one survey (WMO 2006a), only about one-third of the 86 member states surveyed reported well-established national flood forecasting and warning services, with the remainder reporting intermediate, basic, insufficient or no services. Where there were problems this was for a range of reasons including a lack of observational data or technical issues or a lack of institutional capacity.

These types of issues are not just specific to flood forecasting applications and can potentially impact upon all aspects of the forecasting chain. Manually based systems are therefore still widely used, and even in more automated systems, it is still vital to regularly visit gauges to download data loggers and check calibrations and for maintenance and repairs. Indeed, many hydrological services continue to employ gauge readers at automatic sites – at least on a part-time basis – for site maintenance and site security and to provide backup in case instruments fail.

1.1.3 Disaster Risk Reduction

The terminology surrounding early warning systems, natural hazards and contingency planning varies between countries but one concept that is widely used is the disaster risk management cycle. This takes many forms and Fig. 1.2 shows an example for the case of droughts, and Table 1.3 lists some typical aspects for flood warning applications. More generally UN/ISDR (2006) notes that for early warning systems, the following four elements need to be considered:

- Risk knowledge – are the hazards and the vulnerabilities well known? What are the patterns and trends in these factors? Are risk maps and data widely available?
- Monitoring and warning service – are the right parameters being monitored? Is there a sound scientific basis for making forecasts? Can accurate and timely warnings be generated?

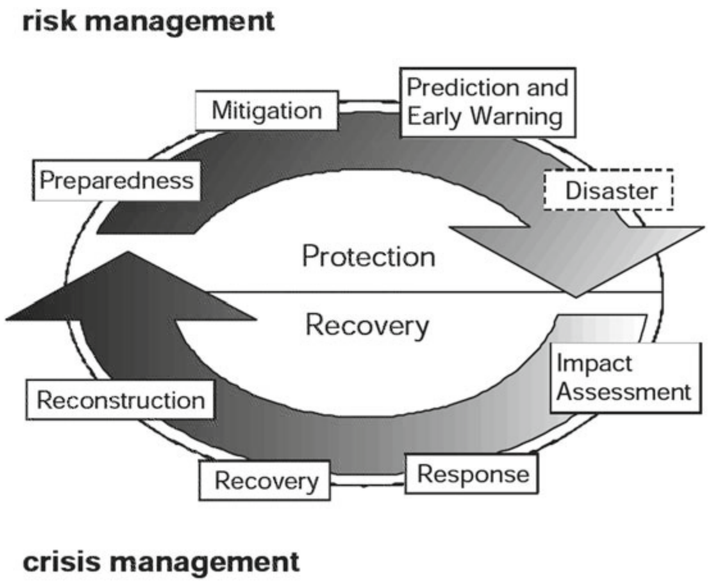


Fig. 1.2 The cycle of disaster management (National Drought Mitigation Center, University of Nebraska-Lincoln; Wilhite and Svoboda 2005)

Table 1.3 Some typical examples of activities within the disaster risk management cycle for flood warning applications

Item	Examples
Preparedness	Lesson-learned/post-event reviews, contingency planning, flood risk assessment, flood modelling, community engagement, public-awareness/outreach activities, media liaison, tabletop, functional and full-scale emergency response exercises, training, capacity building, forecast verification studies, improving monitoring and forecasting systems, research and development, financial/investment planning
Monitoring and forecasting	Monitoring meteorological and catchment conditions, running forecasting models, gathering information from staff on site regarding the flood threat and impacts and from the public and volunteer 'spotters'; for example, sending images and reports to base using smartphones and text messages
Warning	Interpreting the available observations and forecasts and then if appropriate issuing a flood watch or warning in collaboration with civil protection authorities, the emergency services and community leaders
Response	Search and rescue, evacuation of areas at risk, flood-fighting measures to try to reduce the extent of flooding such as raising temporary barriers or using sandbags, lowering (drawing down) reservoir levels, diverting flows
Recovery	Restoration of water, power and other essential services, medical treatment/monitoring, emergency repairs to critical infrastructure, shelter management and logistics
Mitigation	Longer-term measures to repair damage to properties and critical infrastructure, restore livelihoods and help to reduce the future risks from flooding

- Dissemination and communication – do warnings reach all of those at risk? Are the risks and warnings understood? Is the warning information clear and useable?
- Response capability – are response plans up to date and tested? Are local capacities and knowledge made use of? Are people prepared and ready to react to warnings?

Response plans – often called contingency plans – are a key aspect and amongst other objectives serve to clarify the legislative framework, the roles and responsibilities of organisations and the criteria for issuing warnings. Typically in a well-developed contingency planning framework, all relevant government departments, emergency response agencies and local authorities will have plans in place, together with critical infrastructure operators, businesses and the communities at risk. However, as with the technical aspects of a forecasting system, the extent to which this is possible in part depends on institutional capacity, funding and the legislative environment (e.g. Table 1.4).

An important development in recent years has been a move towards disaster risk reduction rather than crisis management. For example, most national governments were signatories to the UN/ISDR Hyogo Framework in 2005, and some key priorities for action for its successor, the Sendai Framework for Disaster Risk Reduction (UN 2015) from 2015–2030, are:

- Understanding disaster risk
- Strengthening disaster risk governance to manage disaster risk
- Investing in disaster risk reduction for resilience
- Enhancing disaster preparedness for effective response, and to "Build Back Better" in recovery, rehabilitation and reconstruction

More generally a community-based or people-centred approach is widely advocated in which those affected play a key role in the design and operation of warning systems (e.g. Basher 2006, Drabek 2000, UN/ISDR 2006, APFM 2006, WMO 2005, 2006b, Parker and Priest 2012). This is sometimes called an end-to-end forecasting and warning system (e.g. WMO 2012b) or one which ensures last-mile connectivity. Neglecting these aspects is often a significant factor in warning systems not performing as expected; for example, in the context of flood warning, FCDMC (1997) notes that:

Table 1.4 Comparative examples of disaster reduction capacities in richer and poorer countries (DFID 2004)

Richer countries	Poorer countries
Have regulatory frameworks to minimise disaster risk which are enforced	Regulatory frameworks are weak or absent, and/or the capacity to enforce them is lacking
Have effective early warning and information mechanisms in place to minimise loss of life	Lack comprehensive information systems linked to pre-emptive response
Have highly developed emergency response and medical care systems	Divert funds from development programs to emergency assistance and recovery
Insurance schemes spread the burden of property losses	Those affected bear full burden of property losses and may lose livelihoods

A common frustration among operators of flood warning systems is the difficulty in evolving from a data collection and monitoring system to one that saves lives and property from flood threat

In that regard, national flood warning guidelines for Australia (Australian Government 2009) note that 'the critical issues in developing and maintaining such a system are:

- it must recognise and satisfy the warning needs of the flood-liable community by ensuring the community is involved in system design and development
- it must incorporate all relevant organisations and be integrated with floodplain and emergency management arrangements
- it must be capable of operating for both 'routine' and severe flood events, and
- each agency involved in the system must accept ownership of it and work co-operatively with other agencies to improve its operation'

Similar considerations apply to other types of disaster, such as droughts and pollution incidents. In particular, the vulnerability of specific groups needs to be considered and typically depends on a range of physical, social, economic and environmental factors; for example, one definition is that vulnerability relates to 'the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard' (UN/ISDR 2009).

Chapters 7, 8, 9, 10, 11, 12 and 13 include some further discussion of these issues for specific applications, whilst the remainder of this chapter provides an introduction to the technical aspects of operational forecasting (Sect. 1.2) and forecast interpretation (Sect. 1.3). Box 1.1 also provides an introduction to one of the key concepts in hydrological modelling, namely, the hydrological cycle.

Box 1.1: The Hydrological Cycle

Hydrometeorology is often defined in terms of the hydrological cycle (or hydrologic cycle in North American terminology) as illustrated by the following examples and Fig. 1.3:

- *[Hydrometeorology is]* an interdisciplinary science involving the study and analysis of the interrelationships between the atmospheric and land phases of water as it moves through the hydrologic cycle (NOAA 2015)
- *[Hydrometeorology is the]* study of the atmospheric and land phases of the hydrological cycle, with emphasis on the interrelationships involved (WMO 2012a)

Rainfall is usually the main influence on river flows although spring flows from aquifers and snowmelt in mountain regions play a role in some river basins. Other key components in the water balance include infiltration and percolation to deeper soil layers and artificial influences from abstractions and discharges; for example, for water supply, irrigation or hydropower operations. Typically river flows reach the sea over timescales of hours to weeks, although in some cases water remains in storage for months or more such as in aquifers, snowpack or large lakes and reservoirs.

(continued)

Box 1.1 (continued)

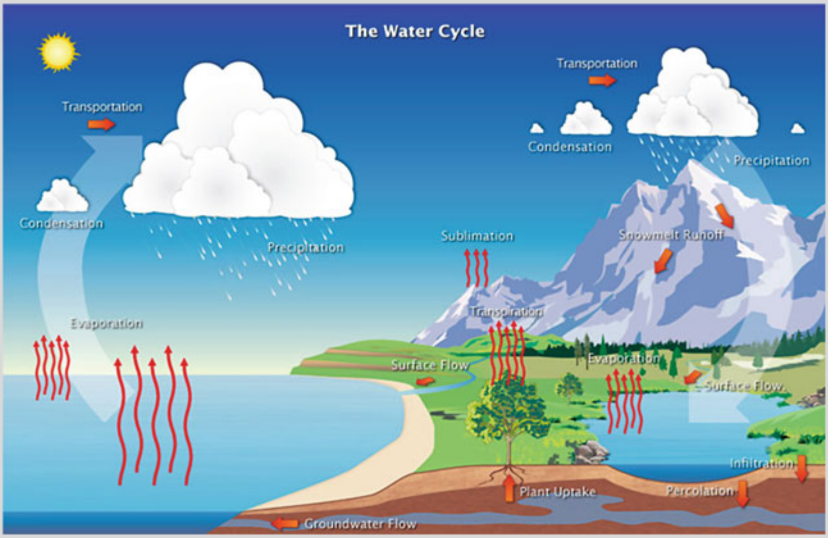


Fig. 1.3 Illustration of Earth's water cycle (Source: NOAA/National Weather Service JetStream – Online School for Weather)

The main driver of this process is solar radiation and the resulting atmospheric circulation. This causes water vapour to return to the atmosphere via evaporation from open water surfaces and evapotranspiration from crops, forests and natural vegetation. Clouds form and the cycle is then repeated as rainfall and other types of precipitation occur, where the term precipitation is used to describe water in its solid and liquid states, such as rainfall, snow or hail. Convective and orographic effects are often key factors in the formation of clouds due to the uplift caused by heating of the land surface and as air flows over hills and mountain ranges.

Chapter 5 provides more background on the surface water and groundwater aspects of the hydrological cycle. The importance of each component depends on a range of factors including geological formations, soil types, artificial influences and the local climate. For example, Fig. 1.4 shows some typical rainfall regimes around the world. These range from high-latitude regions with permanent snow cover to desert regions with little or no annual rainfall, together with mountain regions where the annual snowmelt is a significant contributor to regional water resources.

(continued)

Box 1.1 (continued)

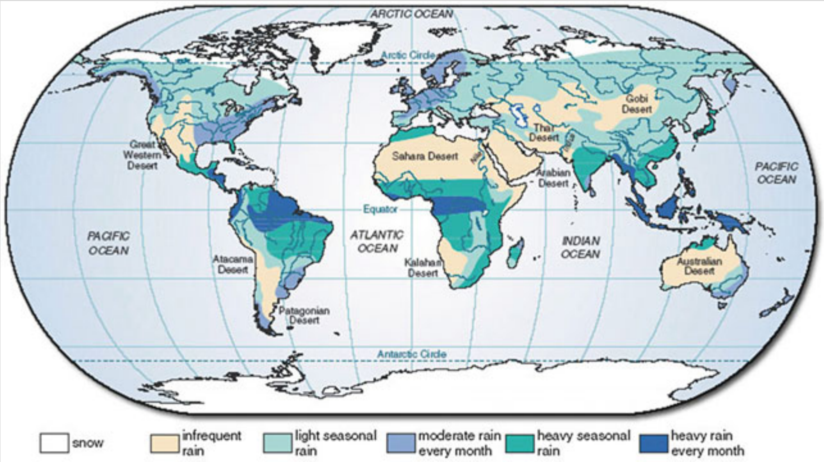


Fig. 1.4 Map showing world rainfall (© Open University, Halliday and Davey (2007), http://www.open.edu)

Internationally the highest annual total rainfall probably occurs in the Cherrapunji area in India where the mean value is about 11–12 m/year and values have exceeded 26 m (e.g. WMO 2009). These extremes are linked to the annual monsoon on the Indian subcontinent which is caused by variations in the 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 onshore.

1.2 Operational Forecasting

1.2.1 Meteorological Forecasting

Table 1.5 summarises the main modelling techniques which are used in meteorological forecasting applications. Although definitions vary, forecasts are often described as short-range for lead times up to 3 days ahead and as medium-range for 3–10 days ahead, whilst extended and long-range forecasts extend to seasonal and longer time periods (WMO 2012c).

Nowcasting was one of the earliest approaches, although the original manually based techniques have largely been replaced by automated systems, at least for precipitation forecasts. At longer lead times, similar techniques are used to forecast the track and landfall of tropical cyclones, which are known as hurricanes in coastal waters off the Americas and typhoons in east and southeast Asia (e.g. Fig. 1.5). Similarly statistical methods are well established with the first applications dating back to the 1920s; typically these make use of the linkages (or ‘teleconnections’)

Table 1.5 Summary of some key meteorological forecasting techniques

Technique	Typical maximum lead time	Basis of method
Nowcasting	Up to several hours ahead	Extrapolation of the motion of weather radar and/or satellite-based rainfall intensity observations, increasingly guided by, or blended with, the outputs from numerical weather prediction models. Also, manual or automated extrapolation of other parameters such as fog
Numerical Weather Prediction (NWP)	Days to months ahead	Three-dimensional modelling of the atmosphere on a horizontal grid and vertical layer basis, accounting for mass, momentum and energy transport and transfer at the land and (in some cases) the ocean surfaces and initialised using observations from a wide range of land-based (weather radar, weather station, etc.), oceanographic (weather stations on buoys, boats, etc.), atmospheric (aircraft, radiosonde, wind profiler, etc.) and satellite-based observation systems
Statistical techniques	Weeks to months ahead	Multiple regression and other statistical techniques linking future weather to indicators or predictors representing the strength of oceanic and atmospheric phenomena such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO)

See Chap. 4 for further details

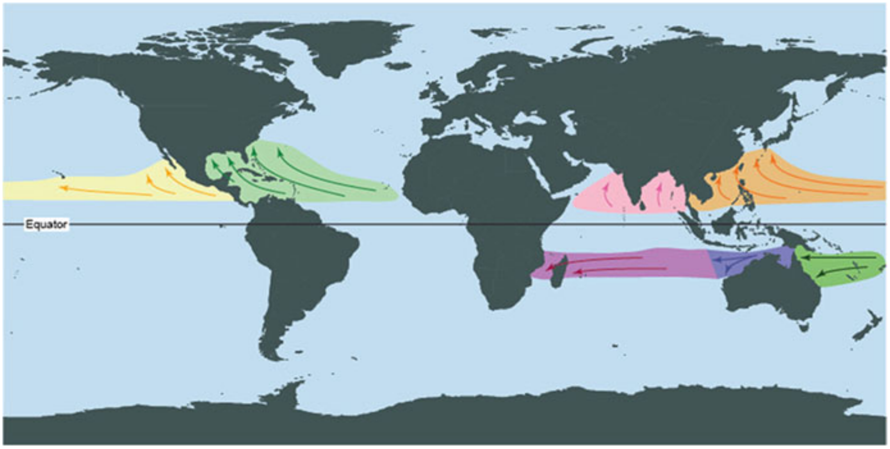


Fig. 1.5 Typical cyclone tracks (Source: NOAA, National Oceanic and Atmospheric Administration)

which are thought to exist between some atmospheric phenomena and ocean conditions, as discussed further in Box 1.2.

However, numerical weather prediction is perhaps the most important approach of all, although it is important to note that not all national meteorological services or centres (NMCs) have the capability to operate these types of model. For this reason under the auspices of WMO, several regional and global centres have been designated which share model outputs with other member states through WMO and other channels. Initiatives such as the Severe Weather Forecasting Demonstration Project (WMO 2010) provide another way of sharing expertise, and the stated objective is to 'improve severe weather forecasting services in countries where sophisticated model outputs are not currently used' through the following general approach:

- global NWP centres to provide available NWP products, including in the form of probabilities
- regional centres to interpret information received from global NWP centres, run limited-area models to refine products, liaise with the participating NMCs
- NMCs to issue alerts, advisories, severe weather warnings; to liaise and collaborate with Media, and disaster management and civil protection authorities; and to contribute to the evaluation of the project

The first project began in Southern Africa in 2006 with subsequent projects in Eastern Africa, the Southwest Pacific Islands and Southeast Asia, with others at the planning stage. For example, in Southern Africa, this has included implementation of a high-resolution model across the region as part of a collaboration between the South African Weather Service, national meteorological services and the UK Met Office.

The term 'limited-area model' here refers to a model which is typically of national or regional extent. In operational use this then requires lateral boundary conditions to be provided by a coarser-scale regional or global model, as illustrated in Fig. 1.6. For each model run a set of initial conditions is required, which is usually based on the outputs from the previous model run and recent observations. This initialisation stage – called data assimilation – is a complex task which normally accounts for a significant proportion of the time between each forecast run. Due to the complexities of this process, and of the models themselves, the most advanced meteorological services use some of the most powerful supercomputers available.

In recent years, ensemble forecasting techniques have become standard practice in numerical weather prediction. The aim is to assess the uncertainty in forecasts due to uncertainties in initial conditions and – in some cases – other factors such as the model parameterisation schemes. Typically about 10–50 ensemble members are generated alongside the deterministic model run, and the outputs are available to forecasters using a variety of map-based and graphical formats.

These types of outputs are increasingly used in hydrological applications as discussed in Sect. 1.3 and later chapters. However, values are often post-processed first to provide a better representation of conditions at the locations and scales of interest. The main techniques include dynamic downscaling, statistical post-processing and weather-matching or analogue techniques (see Chap. 4). For example, statistical post-processing techniques have been used in the National Weather Service in the USA for decades, and many meteorological services and private-sector forecasters use these types of techniques to provide tailor-made (or 'added-value') forecast products for specific users such as airport or wind farm operators.

Due to computational limitations, there is usually a trade-off between the horizontal grid scale, the forecast length (maximum lead time), the number of ensemble members and the model run interval. In the early days, the grid resolutions were such that only the largest-scale features of the atmosphere could be predicted with any confidence. Even in the 1990s the typical grid scales in local or regional models were still about 10–20 km which was often too coarse for hydrological applications.

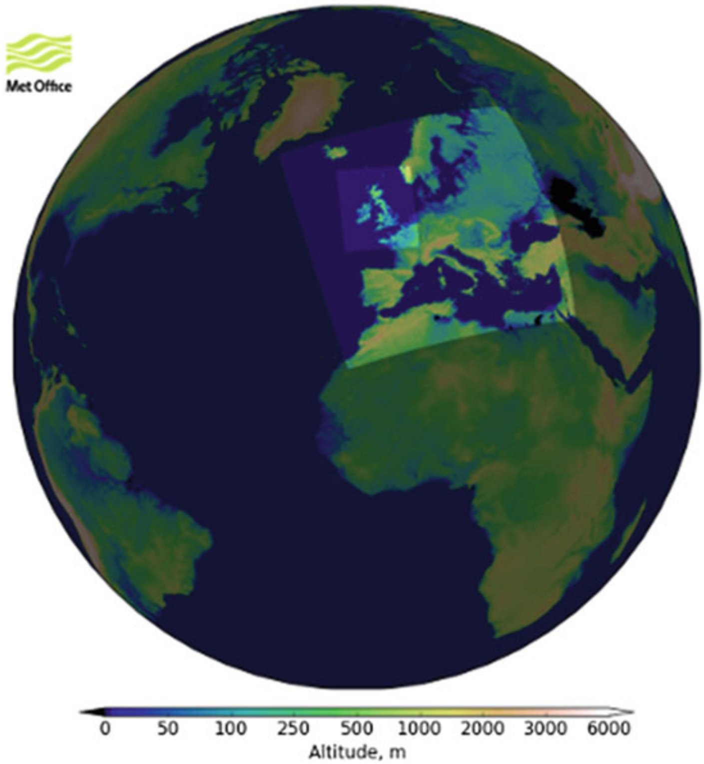


Fig. 1.6 A number of numerical weather prediction models are run at the Met Office (© the Met Office 2015, Contains public sector information licensed under the Open Government Licence v1.0)

However, in recent years, there have been step-changes in resolution meaning that models are now much better able to represent smaller-scale effects such as convectively driven rainfall. Some other key developments have included improvements to data assimilation schemes to make use of a wider range of types of observation systems – such as weather radar observations – and improvements in the representation of land-atmosphere processes. The latest short-range models typically use grid scales in the range 1–2 km and often form part of a suite of models for different domains and lead times, as illustrated in Table 1.6. Here GCMs are normally used for modelling the impacts of climate change for years to decades ahead and consider additional processes which are important at these timescales such as the carbon cycle and the influences of land-use changes.

Whilst using a hierarchy of models has been the general approach for 2–3 decades or more, a long-term aim in many meteorological services is to develop so-called 'seamless' forecasting systems and products as illustrated in Fig. 1.7 (e.g. Seo and Demargne 2008; WMO 2011b). For example, the Met Office (Met Office 2015) notes that some benefits of a seamless forecasting system *include*:

Table 1.6 Hypothetical example of a suite of models operated by a national meteorological service (2010–2015 approximately)

Model	Description
Nowcasting model	15 min estimates on a 1–2 km grid to lead times of 6–8 h (20–50 ensemble members)
Limited area model	1–3 hourly runs on a 1–2 km grid to lead times of 24–36 h (10–20 ensemble members)
Regional model	6 hourly runs on a 10–20 km grid to lead times of 5 days (20–50 ensemble members)
Global model	6–12 hourly runs on a 20–40 km grid to lead times of 15 days (20–50 ensemble members)
Seasonal model	Weekly or monthly runs of the global model for lead times of several months (20–50 ensemble members)
General Circulation Model (GCM)	A global-scale model operated on demand on a 50–300 km grid for run lengths of years to decades (20–50 ensemble members)

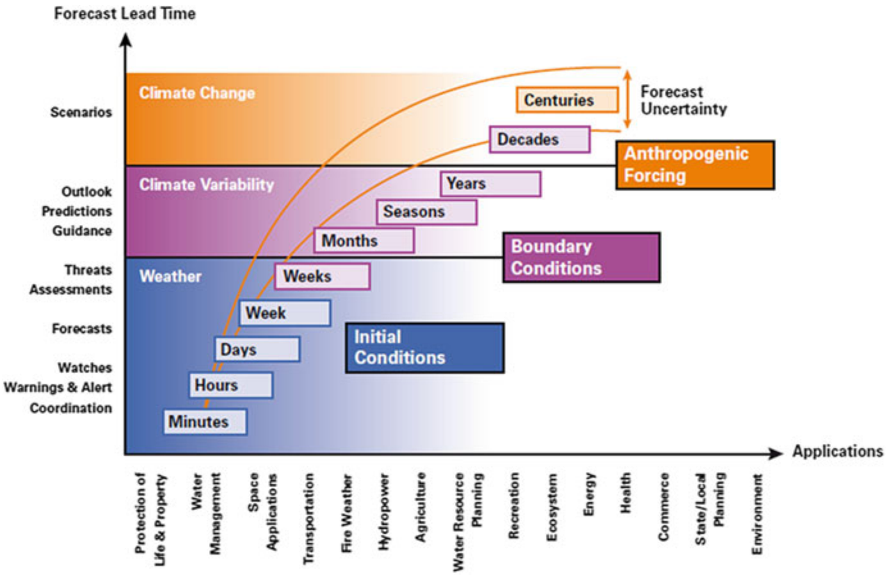


Fig. 1.7 Schematic diagram showing the challenges of developing 'seamless' products and services and the available climate information and gaps (Source: National Oceanic and Atmospheric Administration; in WMO 2011b, courtesy of WMO)

- Efficiency – by developing only one system, duplicated effort is reduced
- Understanding – a seamless system allows us to learn about climate model performance and error growth from well constrained, observed and initialised shorter-range predictions
- Confidence – using the same model at different resolutions gives us confidence that the driving mechanisms within models are consistent with each other