Kevin Sene

Hydro-meteorology

Forecasting and Applications

Third Edition

Springer

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Preface to the Third Edition

As I reflect on writing this third edition of *Hydrometeorology: Forecasting and Applications*, it is interesting to consider what has changed in the eight years since the last edition was published.

As before, Part I—Techniques—introduces the main techniques used in monitoring, forecasting and warning, with a focus on what is used operationally and what might be in the not too distant future. Here some of the main advances have been technological, with phased array weather radars ever closer to operational use and satellite missions such as SWOT potentially opening up more hydrological applications of remote sensing.

At the other extreme, low cost instrumentation offers the possibility to extend monitoring networks into locations not financially feasible before, such as in urban areas for surface water flood warnings and extending the reach of community-based early warning systems. Smartphone and web applications also facilitate crowdsourcing to provide real-time feedback on what is happening on the ground during a storm, flood or drought.

The chapters on meteorological observations, catchment monitoring, hydrological forecasting and forecast interpretation have been significantly expanded to include some of these themes, with the latter now called impact-based forecasting and warning. As before, the focus is on key concepts, operational requirements and end-user needs rather than providing step-by-step instructions for which many excellent textbooks and guidelines are available, as highlighted in the text.

In Part II—Selected Applications, it is noted that information technologies such as ‘Big Data’, cloud computing and high-performance computing are also allowing applications that did not seem feasible just a few years ago. These include global scale flood forecasting and water resources modelling systems and the increasing use of process-based models in hydrological applications, such as land surface models. The international WMO/UNDRR ‘Early warnings for all initiative’ is also spurring many developments, with the ambitious aim to protect ‘every person on Earth by early warnings’ by 2027. If the increases in chapter lengths are a suitable indicator, perhaps the main advances have been in flood forecasting and drought early warning, and climate change prediction now has its own chapter.

From an engineering perspective, web-based delivery of data and models is an increasingly attractive option, providing instant access to spatial datasets and forecasts, such as weather radar and ensemble rainfall forecasts, with a managed data storage service as an option. Potential applications include precision (or digital) agriculture, water allocation modelling and flood forecasting. For researchers, community-based approaches to model development are enabling ever greater collaboration and sharing of observations and geospatial data between research teams, helping to focus on key processes rather than data management.

The science continues to advance too, such as in the widespread adoption of Hydrological Ensemble Prediction Systems with advances throughout the modelling chain, such as in downscaling, pre- and post-processing, data assimilation and decision support systems. Thankfully, it is now almost taken for granted that estimates for uncertainty should be available in both observations and model outputs to inform risk-based decision making, albeit still with some challenges in deriving and communicating the results. The international drive towards impact-based forecasts and warnings is also spurring many developments in the techniques used to convey information to end users. Allied to that is an increasing need for meteorologists and hydrologists to work ever more closely with specialists from other fields, such as in the social sciences and behavioural psychology.

From an author's perspective, another very welcome development has been the ever-accelerating move towards open publishing, not just of scientific papers but in the so-called grey literature too, such as in strategy documents, internal technical reports, white papers, operational guidelines and brochures from instrument manufacturers and consulting engineers. These were important sources of information for previous editions too but are now much more readily available and sometimes give additional insights into what is realistic beyond that found in scientific papers.

On that theme, since the last edition, there seems to have been a massive increase in the number of scientific publications each year, making it unrealistic to include more than a selection. And it is perhaps part of the value of books like this that due to space limitations a tightly focused, curated list of references is provided. As before, I've tried to include both significant early papers on a topic and more recent publications that provide insightful reviews or describe major steps forward. Earlier works in particular can be valuable for understanding both how well an idea has stood the test of time and explaining key concepts that tend to now be taken for granted.

Just 3–4 years ago, there might have been no need to mention artificial intelligence, but changes are occurring so rapidly that this is now essential. Of course, data-driven techniques such as artificial neural networks and transfer functions have been used operationally in hydrology since at least the 1990s but have tended to be hidden away behind the scenes. Applications include satellite precipitation estimation, water demand forecasting, hydropower scheduling, data assimilation and flood forecasting. The implications of the latest developments are still being worked through but seem likely to bring dramatic changes in some areas, such as in weather forecasting, image processing and pattern recognition. Potential applications include interpreting crowdsourced information, data validation, multi-sensor product development, and earlier recognition of debris flows, flash floods and droughts.

To sum up, much has changed since the last edition with many exciting developments on the horizon. But for newcomers, it's best not to forget the basics such as trying to understand underlying processes, routinely making reality checks on observations and model outputs, putting time and effort into the choice of model performance metrics, visiting sites to better understand the issues if feasible and most of all working closely with end users to jointly agree on what is operationally feasible and useful.

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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.

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.

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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 UK. 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 organisations 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: B. Golding (1.3). H. Male (2.2), P. Schlatter (2.3), F. Thompson (3.1), M. Budimir (3.2, 7.2, 8.1), K. Stewart (3.3), E. Sprokkereef (8.2), M. Wagemans (12.1), R. Stidson (12.2), B. Cosgrove (13.1), L. Beevers (14.2), and N. Chappell (14.3).

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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:

- Cabinet Office (Fig. 4.3)
- Defra (Figs. 9.8 (part), 9.10)
- Environment Agency (Figs. 7.5, 11.6)
- European Centre for Medium-Range Weather Forecasts (Figs. 4.1, 4.6, 4.7, 4.8)
- European Union (Fig. 10.5)
- Federal Emergency Management Agency (Fig. 7.7)
- International Commission for the Hydrology of the Rhine Basin (Fig. 12.3)
- Lancaster Environment Centre (Fig. 12.4)
- Met Office (Figs. 1.12, 2.7, 2.8, 2.9, 2.10, 3.10, 4.2, 4.3, 7.11, 14.1)
- National Aeronautics and Space Administration (NASA) (Figs. 2.3, 3.12, 12.5)
- National Drought Mitigation Center (Figs. 1.6, 10.1, 10.2, 10.3)
- NOAA/Great Lakes Environmental Research Laboratory
- NOAA/National Weather Service
- National Oceanography Centre (Fig. 8.16)
- National Oceanic and Atmospheric Administration (NOAA) (Figs. 1.1, 1.3, 1.4, 1.8, 1.10, 2.11, 2.12, 2.13, 3.13, 4.5, 5.6, 5.9, 7.8, 7.12, 8.4 (part), 8.18, 9.2, 9.7, 12.6, 13.1, 13.2, 13.3, 13.6, 13.8)
- Office of Science and Technology (Fig. 8.9)
- Open University (Fig. 1.2)
- Practical Action (Figs. 3.5, 3.6, 7.1, 7.2, 7.3, 7.4, 8.6, 8.7)
- Rijkswaterstaat (Figs. 8.11, 8.12, 11.5, 12.2)
- Scottish Environment Protection Agency (Figs. 12.7, 12.8)
- Springer (Figs. 1.5, 2.4, 2.6, 3.4, 3.7, 3.8 (part), 4.4, 5.2, 5.3, 5.7, 5.8, 5.10, 5.11, 5.12. 6.4, 7.6, 7.9, 7.10, 8.3, 8.4 (part), 8.10, 8.13, 8.14, 8.15, 8.17, 9.4, 9.5, 9.6, 9.8 (part), 12.1, 13.5, 13.6)
- Tennessee Valley Authority (Fig. 6.5)
- Urban Drainage and Flood Control District (Fig. 3.14)
- U.S. Army Corps of Engineers (USACE) (Figs. 9.12, 11.4)
- U.S. Department of Agriculture (USDA) (Fig. 3.11)
- U.S. Environmental Protection Agency (US EPA) (Fig. 9.9)
- U.S. Geological Survey (USGS) (Figs. 3.1, 3.2, 3.3, 5.5, 6.1, 6.2, 6.3, 9.11)
- World Meteorological Organisation (WMO) (Figs. 1.9, 1.11, 2.1, 2.2, 5.2, 8.1, 9.3, 10.4, 11.3, 13.7)

Contents

Part I Techniques

Part II Selected Applications

Chapter 1
Introduction

Abstract Hydrometeorological forecasts are used in a wide range of applications such as early warning systems, reservoir operations, managing pollution incidents 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 operational meteorological and hydrological forecasting techniques, and introduces concepts such as climate services, value chains and risk-based approaches to decision-making. Other topics include the increasing roles of citizen science and artificial intelligence. Flood, drought and other early warning systems are considered too, with a particular focus on end-to-end warning systems, including the WMO/UNDRR Early Warnings for All (EW4All) initiative.

Keywords Hydrometeorological forecasting · Meteorological forecasting · Flood forecasting · Drought early warning systems · Risk-based decision making · Early warning systems · Citizen science · Value chains · End to end warnings · Early warnings for all · EW4All

1.1 Background

1.1.1 What Is Hydrometeorological Forecasting?

Hydrometeorology is an applied science concerned with the way that variations in the weather and climate affect rivers, reservoirs and other water bodies, such as lakes and wetlands. The types of questions a hydrometeorologist might ask are will a flood occur after this heavy rain, or will this dry period become a drought, or will this reservoir have enough water to last the summer?

The World Meteorological Organisation (WMO 2012a) defines hydrometeorology as the study of ‘the atmospheric and land phases of the hydrological cycle, with

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emphasis on the interrelationships involved.' Box 1.1 describes the hydrological cycle, which is also called the water cycle.

This book deals with a key aspect of hydrometeorology, namely forecasting, which aims to provide specific estimates—no matter how uncertain—for the timing, location and magnitude of events or conditions in the future. Applications include providing early warnings for potentially dangerous situations such as flash floods and river pollution incidents, and assisting with day-to-day operations, such as irrigation scheduling and hydropower operations. Longer lead time applications include water resources planning, drought early warning systems and climate change impact assessments.

As the lead time increases, the uncertainty in forecasts increases too, so it is good practice to include an estimate of uncertainty with forecasts. This can lead to improved decision-making, particularly in challenging situations such as whether to evacuate residents from a town in advance of a flood or limit water use in the run up to a drought. For example, a meteorological service might issue a forecast that there is an 80% probability of rainfall exceeding 150 mm in the next 24 h, or that there is a 45% chance that it will be below normal in the next 3 months. Hydrologists would then use additional models to estimate the chances of flooding or drought, in these two examples.

Impact-based forecasts and warnings assist greatly in this process by interpreting information in terms that are more meaningful to end users. As an example, it is much more useful to name particular streets that are at risk, rather than to say how high river levels will be. Similarly, during a prolonged dry spell, a disaster management organisation would rather know if crop yields are likely to be affected, rather than just how dry it will get. Considerable investigation is often required to build impact-based information into forecasting procedures, requiring close collaboration with other experts such as community representatives, emergency responders, economists and social scientists.

Of course, another key consideration is whether it is technically feasible to provide useful information sufficiently far in advance to take meaningful action. The American Meteorological Society (AMS 2022) defines the forecast lead time as 'the length of time between the issuance of a forecast and the occurrence of the phenomena that were predicted.' In flood forecasting applications, that might be the time between issuing a forecast and river levels first overtopping flood defences, affecting houses and property. Although the boundaries are not clear-cut, some typical ideal lead-time requirements in hydrometeorological applications include:

- Minutes to days ahead—flood warnings, hydropower scheduling, irrigation scheduling, water supply operations, debris flow warnings
- Days to months ahead—drought early warnings, advice on planting/harvesting crops, annual snowmelt forecasts, water levels in a wildlife reserve
- Months to years ahead—river basin management, climate change impact assessments, operating 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.

The spatial scale of a forecast is another consideration and whether the location information provided is sufficiently precise to take meaningful action. Providing flash flood warnings has long been a good example of the challenges, although great advances have been made in recent years, as discussed in later chapters. Table 1.1 gives some further examples, considering both lead time and spatial requirements. Here a sub-catchment is that part of the catchment (or watershed or river basin) above the point at which a forecast is required, which is normally called a forecast or forecasting point.

Many techniques are potentially available to generate and issue forecasts and Table 1.2 summarises the approaches discussed in Part I of this book. The extent to which these are required depends on the application; for example, in a large river catchment, sufficient advance warning of flooding may be possible by modelling the passage of flows from an upstream river gauge, whereas for a small upland catchment the only feasible way to issue warnings in time might be from a rainfall forecast. Demand forecasts clearly would not be required in either of these applications but are often a key input to drought and water resources applications.

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 systems	Individual water supply schemes to 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, hours to days to weeks ahead for harmful algal blooms, and longer term for wider 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, 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. fertilization, pest control), seasonal for planting/harvesting decisions; longer range for investment decisions (see Chaps. 6 and 10)

(continued)

Table 1.1 (continued)

Application	Typical spatial scale	Typical lead time requirements
Navigation	River reaches, canals, lakes, or 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 Chap. 8)
Pollution incidents	Subcatchment, 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	Subcatchment, 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, subcatchment, catchment or regional	Varies from minutes or hours to days ahead for tactical decision making regarding pumping, water 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	Chapter	Description
Meteorological observations	Chapter 2	Observation techniques include raingauges, weather stations, weather radar, satellite precipitation estimates and multi-sensor products
River and catchment monitoring	Chapter 3	Monitoring techniques include river gauges, reservoir gauges, tide gauges, soil moisture sensors, snow sensors, water quality sensors, and satellite-based observations
Weather forecasting and climate prediction	Chapter 4	Forecasting techniques include nowcasting, numerical weather prediction, and statistical methods, plus statistical, weather matching and dynamic post-processing (downscaling) techniques
Hydrological forecasting	Chapter 5	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
Demand forecasting	Chapter 6	Forecasting techniques include empirical, statistical, artificial intelligence and micro-component based approaches for estimating withdrawals (abstractions) for water supply, irrigation, hydropower and other applications
Impact-based forecasting and warning	Chapter 7	Approaches to issuing impact-based forecasts and warnings and taking decisions on the information provided, including ensemble, risk-based and threshold-based techniques and decision support systems,

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 example from the National Weather Service's online glossary:

> [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

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, such as for water supply, irrigation or hydropower operations. River flows normally 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. Figure 1.1 illustrates the main processes.

The main driver for 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; here the term precipitation is used to describe water in its solid and liquid states, such as rainfall, snow or

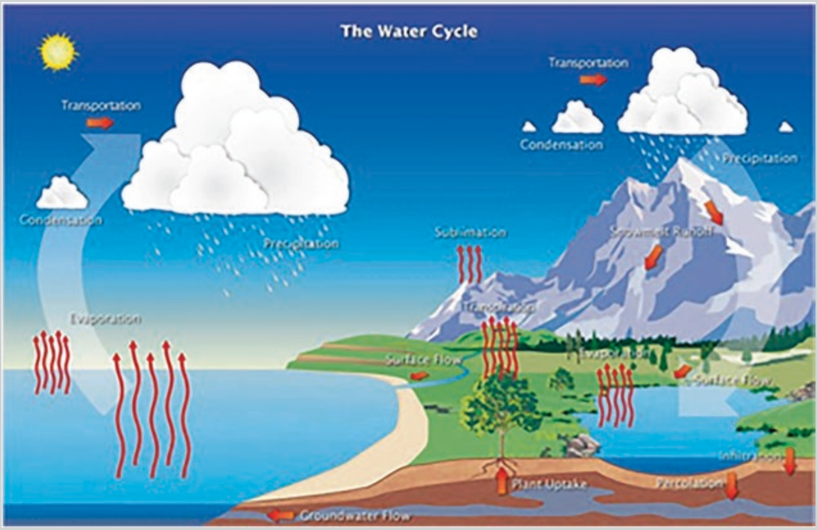

Fig. 1.1 Illustration of Earth's water cycle. (Source: NOAA/National Weather Service JetStream—Online School for Weather)

(continued)

Box 1.1 (continued)

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. 1.2 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. The magnitude of each component can also vary over time due to both climate and human influences (called artificial influences in this book).

Internationally the highest annual total rainfall is thought to occur in the Cherrapunji area in India where the mean value is about 11–12 m/year and annual values have exceeded 26 m (e.g. WMO 2008). 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. In contrast, in some desert regions little or no rainfall has been recorded in recent decades.

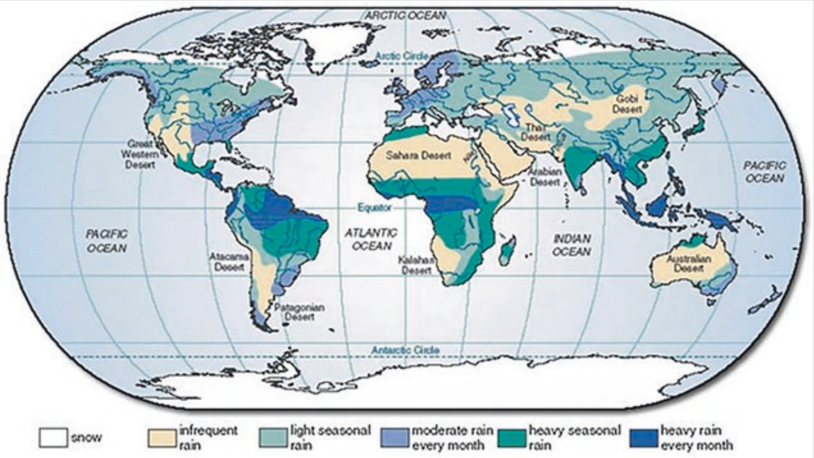

Fig. 1.2 Map showing world rainfall. (© Open University, Halliday and Davey (2007), http://www.open.edu)

1.1.2 Who Produces Hydrometeorological Forecasts?

Within a country or region, several organisations may issue hydrometeorological forecasts for specialist users, such as environmental regulators, water supply managers and river basin authorities. However the definitive publicly available forecasts will probably come from the national meteorological and/or hydrological service.

These terms are defined by the World Meteorological Organisation (WMO) who play a major role in coordinating meteorological observations and forecasts worldwide and helping to improve hydrometeorological forecasting capacity, particularly in less developed countries. It is headquartered in Geneva and is the United Nations specialised agency for meteorology (weather and climate), operational hydrology and related geophysical sciences.

The meteorological contribution is from the national meteorological service and in some countries the two functions are combined, such as with the National Weather Service in the USA and the Bureau of Meteorology in Australia. A common alternative is to establish a joint operations or forecasting centre, such as the Flood Forecasting Centre at the Met Office in the UK, which is staffed by experts from both the Met Office and the Environment Agency. Box 1.2 describes some examples.

The first routine observations in hydrometeorology began in the mid to late nineteenth century, when raingauge networks were established in some countries such as the UK. Systematic river level monitoring typically began a few decades later, sometimes between the two world wars, but in some cases not until the 1950s or 1960s. This of course excludes individual gauges set up at key sites, of which the Roda Nilometer near Cairo is perhaps the most famous example, and was in operation more than a thousand years ago.

Values would typically be recorded manually by paid or volunteer observers at set times each day, with gauge readers or watchmen living on site or recruited from local residents. 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, some of which have been digitised by international data rescue projects in recent years for use in water resources and climate change studies.

During emergencies, observations would often be relayed more frequently by telegraph in the early days, and then by phone call or a handheld or desktop VHF or UHF radio. This general approach is still used in locations where budgets do not allow more automated telemetry systems.

The first public weather forecasting services also began in the nineteenth century, while the earliest river flow forecasting services probably date back to the 1930s. Early hydrological models were crude by today's standards, although one of the earliest techniques, the unit hydrograph, is still widely used in off-line flood estimation studies. Table 1.3 shows some other significant developments since that time.

Cell phone, smartphone and web-based technologies have also revolutionised the options available for issuing warnings and forecasts. This includes in some of the least developed countries, where ownership of basic phones is often surprisingly

Table 1.3 Summary of some key technological developments in monitoring and forecasting techniques

Technique	Chapter	Description
Weather radar	Chapter 2	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.
Satellite observations	Chapter 2	Launch of the first earth-observing satellites in the 1960s, since then used for an ever-increasing range of applications, including the first spaceborne precipitation radar from the 1990s.
Automated river gauges	Chapter 3	Introduction of automated sensors for recording river, lake, reservoir and tidal levels, such as float-in-stilling well devices in the early days and pressure transducers and bubbler gauges from the 1990s.
Telemetry	Chapter 3	Introduction 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 UHF or VHF radio or landline-based systems.
Numerical weather prediction	Chapter 4	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.
Distributed hydrological modelling	Chapter 5	Since the 1960s, the operational use of semi-distributed models of entire river basins to forecast floods and more recently of grid-based distributed models for water resources and flood guidance applications.

high, sometimes partly thanks to the efforts of international development agencies. ITU (2023) notes that ‘As of 2022, 95% of the world’s population had access to a mobile broadband network and close to 75% of the population owned a mobile phone.’… while also noting that there are significant gaps in coverage, particularly in Africa and parts of the Americas.

Through the auspices of the WMO, national meteorological and hydrological services also benefit from observations shared internationally within the WMO Integrated Global Observing System, which is discussed in Chap. 2.

Due to all these developments, a modern-day hydrometeorological forecasting system normally makes use of many sources of data and types of models and provides information that underpins a wide range of forecasting products and services. Most forecast centres are staffed year-round with additional staff on call during emergencies, at which time operations become around the clock (24/7) if budgets allow. Larger centres have staff on duty at all times.

Outside emergencies, other hydrological activities include staff training, developing models, liaison with professional partners, developing and improving operational procedures and hydrometry, which is the measurement of river conditions. Linked to this there is usually also a considerable information technology, communications, and instrumentation infrastructure to maintain and improve to support these operations. WMO (2011a), Pagano et al. (2014), Adams and Pagano (2016) give more insights into the many tasks performed and operational systems around the world.

This description of course applies to some of the most developed national meteorological and hydrological services and a recent survey (WMO 2021b) suggests a more varied picture. Based on questionnaires completed for 101 WMO Member countries, some key conclusions included:

- There is inadequate interaction among climate services providers and information users in 43% of WMO Members
- Data is not collected for basic hydrological variables in approximately 40% of WMO Members
- Hydrological data is not made available in 67% of WMO Members
- End-to-end riverine flood forecasting and warning systems are absent or inadequate in 34% of WMO Members that provided data—with only 44% of Members' existing systems reaching more than two-thirds of the population at risk
- End-to-end drought forecasting and warning systems are lacking or inadequate in 54% of WMO Members that provided data—with only 27% of Members' existing systems reaching more than two-thirds of the population at risk

And noted that:

Investments in real-time observing networks, weather forecasts, early warnings and climate information make economic sense' with dividends including:

- avoided losses—reliable and accurate early warning systems save lives and assets worth at least 10 times their cost
- optimized production—the estimated annual benefits of improved economic production through the application of weather and climate prediction forecasting in highly weather/climate-sensitive sectors; and
- improved long-term strategic response to climate change

International initiatives such as the Flash Flood Guidance System (FFGS) with Global Coverage are helping to fill in some of these gaps and are discussed in later chapters. A later review (UNDRR/WMO 2023) notes subsequent improvements with more than half of countries reporting Multi-Hazard Early Warning Systems.

Box 1.2: National Hydrological Services

In most countries the national meteorological service is the lead organisation for meteorological observations and forecasting. However, in hydrology arrangements are often more diverse and in addition to the national authorities other organisations may operate their own monitoring networks and—in some cases—forecasting models too. These include:

- Environmental regulators—for flood warning purposes and for monitoring river abstractions and discharges, environmental flows and water quality
- Hydropower operators—to assist with deciding on water releases from reservoirs for hydropower generation

(continued)

Box 1.2 (continued)

- Irrigation scheme operators—to assist with irrigation scheduling and scheme management
- Navigation authorities—to assist in operating control gates, water transfer schemes and issuing navigation warnings
- River basin authorities—who may have responsibilities for major dams and flood warning and in some cases operate transboundary networks of river gauges
- Water utilities—to support reservoir operations and river abstractions and discharges

The activities of a forecaster typically extend far beyond preparing and running models and as Pagano et al. (2014) note:

> Hydrologists also coordinate with the producers of other forecasts (e.g.,meteorologists), review data, interpret model output, assess forecast confidence, consider nonmodeled factors (including anecdotal information), coordinate with water managers whose actions both depend on and affect river flow, translate model output into the decision-maker's context, and respond to user requests.

The USA provides a good example of the diversity of approaches possible. At a national level, the National Weather Service has responsibility for both weather and hydrological forecasting, with more than 120 Weather Forecast Offices (WFOs) and 13 River Forecast Centers (RFCs). Additional support comes from the National Centers for Environmental Protection (NCEP) and the National Water Center. The National Weather Service is also responsible for operating the USA's national network of 160 S-band dual polarisation weather radars (see Chap. 2). These organisations are all part of the National Oceanic and Atmospheric Administration (NOAA) which is part of the US Department of Commerce.

The main functions of River Forecast Centres include (Hartman and Schaake 2014):

- Continuous hydrometeorological data assimilation, river basin modeling, 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

Figure 1.3 shows their locations and Fig. 1.4 illustrates some of the products issued.

(continued)

Box 1.2 (continued)

Fig. 1.3 National Weather Service River Forecast Centers in the United States. (http://www.cnrfc.noaa.gov/)

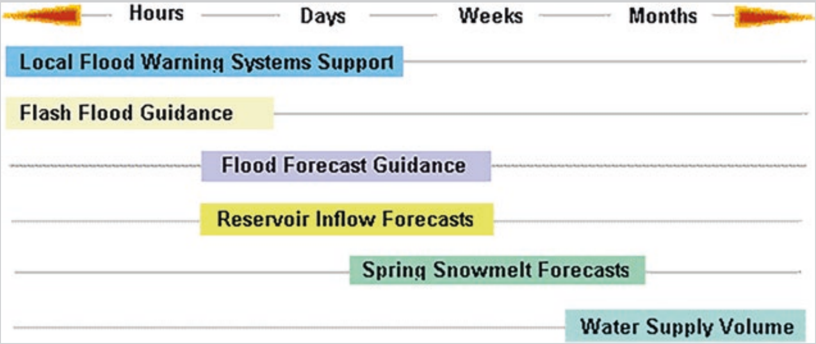

Fig. 1.4 Illustration of the range of forecasts provided by River Forecast Centers at different lead times. (www.noaa.gov/jetstream/rfcs)

(continued)

Box 1.2 (continued)

Adams (2016) provides a more detailed overview. River Forecast Centers typically work in partnership with other federal, state and local organisations, including:

- USACE—the US Army Corps of Engineers, primarily related to dam operations, flood control and navigation
- USBR—the US Bureau of Reclamation, primarily related to dam, hydropower and irrigation canal operations in the western USA
- USGS—the US Geological Survey, which has a key role in monitoring, mapping and modelling to support decision-making on environmental, resource and public safety issues

In particular, the USGS operates more than 8000 telemetered river gauges across the USA under the National Streamflow Information Program (see Box 3.1 in Chap. 3). Local flood warning systems are also common in the USA, often with extensive automated networks of river gauges, raingauges and weather stations reporting observations to a central operations centre, as discussed in Box 3.3 in Chap. 3.

1.1.3 Early Warning Systems

While hydrometeorological forecasts are widely used day-to-day, such as in reservoir operations, much of the current international focus is on early warning systems, with the view that everyone has the right to early warnings of natural hazards.

Some successes in recent decades include the Cyclone Preparedness Programme in Bangladesh, which was initiated in the 1970s and has saved many lives (see Chap. 7) and the establishment of flood warning services in many countries, reducing the occasions on which floods arrive unannounced. Box 1.3 introduces the idea of a value chain, showing how there are several stages in an early warning system, each of which has to work during the pressure of an event for a warning to be useful and acted upon.

Figure 1.5 shows a simple example of the use of rainfall forecasts to help with issuing a flood warning, for the idealised case of an isolated storm leading to a rapid rise in river levels. Here the risk of flooding is assessed by comparing the forecast levels with a predefined flood alert value called a threshold, which in this case is anticipated to be exceeded.

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 or overestimate levels, and would organisational procedures allow a warning to be issued on the basis of a forecast alone, which in meteorology is sometimes called a 'warn-on-forecast' approach. These more general issues of forecast interpretation and forecast verification are discussed in later chapters.