Flash Floods

Kevin Sene

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Forecasting and Warning

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Preface

In the media, the term ‘flash flood’ often conjures up images of a wall of water arriving out of nowhere in a previously dry river bed. Floods of this type do occur, particularly in arid and semi-arid regions, and can present a considerable risk to people and infrastructure. However, the scientific definition is rather wider and is often presented in terms of the time delay between heavy rainfall and the onset of flooding. Several related types of rapid onset or ‘short-fuse’ events are usually included, such as debris flows and the flooding caused by ice jams, dam breaks, levee breaches and surface water in urban areas.

To reduce the risk from flash floods, warning systems are widely used alongside structural measures such as flood defences or levees. For example, an accurate and timely warning can alert people to move to safer locations and provide civil protection authorities with more time to prepare an effective response. When telemetry-based flood warning systems were first introduced several decades ago, a catchment response time of six hours was typically quoted as the minimum for providing operationally useful warnings. However, in many countries, technological and procedural improvements now allow a warning service to be provided where times are shorter than this.

However, despite these advances, there are still many opportunities to reduce time delays further and to improve the accuracy and coverage of warnings; for example through improvements to flood forecasting models and faster warning dissemination techniques. For natural hazards, wider community involvement is now also seen as essential to improve the effectiveness of warning systems, using what is often called a people-centred, total or end-to-end approach.

This book provides an introduction to these various topics. The warning process is often considered to consist of monitoring, forecasting, warning and preparedness components and that format is adopted here. Part I discusses the main techniques which are used whilst Part II considers a range of applications. Some general background is also provided on approaches to flood risk management. The topic of emergency response – in itself a major subject – is also discussed briefly where this impacts on the approaches used for providing flash flood warnings.

The use of lower cost, less technically advanced systems is considered throughout; for example, the use of community-based warning systems in rural areas.

Within the general area of monitoring, precipitation measurement often plays a key role, including raingauge, weather radar and satellite-based observations. For example, some recent developments which are considered include dual polarization weather radar and multi-sensor precipitation estimates. Methods for monitoring catchment conditions are also discussed, including river gauges and techniques for estimating snow cover and soil moisture.

To help improve warning lead times, flash flood forecasting models are also widely used. The first operational applications were often empirically based, using river level correlations and tabulated relationships between rainfall and flows. However, nowadays more options are available and the types considered include conceptual, data-driven and physical-conceptual rainfall-runoff models and hydrological and hydrodynamic flow routing techniques. Simpler rainfall threshold and flash flood guidance approaches are also discussed. Rainfall forecasts are also useful in providing early indications of the potential for flash flooding and, in recent years, there has been a step change in the spatial resolution and accuracy of model outputs. Several recent developments are therefore discussed including probabilistic nowcasting techniques, mesoscale data assimilation and decision support systems for severe storms.

The two remaining components in the warning process – flood warning and preparedness – are closely linked and some key principles are introduced. These include procedural issues such as developing flood response plans and performance monitoring, and technological developments such as the use of social media and multimedia systems when issuing warnings. Web-based decision support tools are also increasingly used to share information between flood warning and emergency response staff. Taken together, these developments help to make it possible to issue flash flood warnings more quickly than in the past and to more people, who in turn have a greater awareness of the actions to take.

The application of these techniques is discussed in Part II. This considers flash floods from a number of sources, including rivers, ice jams, debris flows, urban drainage issues, dam breaks, levee breaches and glacial lake outburst floods. The general principles used are the same throughout but with some additional technical and operational challenges specific to each type of flooding. These include the development of techniques for monitoring debris flows and assessing the flood risk in urban areas, and for estimating the impacts of dam breaks and levee breaches. Several examples of operational systems are also discussed.

The final chapter provides a brief summary of some current research themes relevant to flash flood forecasting and warning systems. These include monitoring techniques such as phased array weather radar, adaptive sensing and particle image velocimetry, and a range of more general developments in rainfall and flood forecasting. Several recent advances in probabilistic forecasting are also discussed, including the issue of how best to communicate the outputs to decision-makers. Overall, these developments raise a number of intriguing possibilities for further improvements in the flash flood warning process in future years.

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As 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. For example, 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): G. Blöschl (8.3), S. Cannon (9.1), B. Cosgrove (5.2, 8.2), B. Hainly (3.1), P. Javelle and colleagues (8.1), M. Maki (10.1), E. Morin (12.4), O. Neussner (1.2), D. Pepyne (12.2), B. Pratt and colleagues (1.1), M. Ralph (4.1, 12.1), P. Schlatter (2.1), A. Shrestha (11.2), M. Sprague (6.1), B. Vincendon (12.3) and J. Zhang (2.3). The second half of Box 4.1 is also adapted from text provided by M. Ralph.

Others who allowed figures to be used (with the figure numbers included in brackets) included: G. Blöschl (8.8), R. Cifelli and M. Ralph (12.1), B. Cosgrove (5.4), W. Empson and J. Hummert (11.2), I. Fujita and M. Muste (12.3), B. Hibbert (2.4 part), V. Meyer (7.1, 8.3), T. Patterson (11.1 part), M. Peura (2.7), P. Rossi and K. Halmevaara (Fig. 4.11), E. Rudel (3.7), D. Sills (12.4) and J. Zhang (2.6). Note that Figures 8.8, 8.12, 8.13 and 8.14 are 'Copyright © International Association for Hydro-Environment Engineering and Research' and 'Reprinted by permission of Taylor & Francis Ltd, www.tandfonline.com on behalf of The International Association for Hydro-Environment Engineering and Research.'

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Contents

Chapter 1
Introduction

Abstract Flash floods are often characterized as rapidly developing events which leave little time for people to take actions to reduce damage to property and the risk to life. Whilst the main cause is usually heavy rainfall, flooding can also arise from ice jams in rivers, dam or levee breaks, and surface drainage issues in urban areas. Debris flows are another closely related hazard. To help to reduce the risk, flood warning systems are widely used, although with a key challenge being the short time available to interpret and act upon rainfall, river and other observations. However, the lead-time can potentially be increased by using rainfall and flood forecasts and making other stages in the warning process more efficient. In some cases, it is also possible to start flood fighting activities to reduce the extent of flooding. This chapter presents an introduction to these topics and reviews some of the definitions of flash floods.

Keywords Flash flood • Flood risk management • Flood warning • Flood forecasting • River flooding • Ice jam • Debris flow • Urban flooding • Dam break • Levee breach • Outburst flood

1.1 Types of Flash Flood

Flash floods are one of the most devastating natural hazards. They are often characterised by deep, fast flowing water which – combined with the short time available to respond – increases the risk to people and property. The main cause is usually heavy rainfall and locations at risk range from desert regions where watercourses are normally dry through to more temperate zones, particularly in mountainous regions. Other natural causes include ice jams and glacial lake outburst floods. Infrastructure-related flooding sometimes also occurs due to dam breaks, surface water flooding in urban areas, and the failure of levees, embankments and other structures.

Table 1.1 illustrates some of the main types and causes of flash floods. For convenience the term 'river flooding' is used although it is important to distinguish this

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Table 1.1 Summary of the some of the main types and causes of flash flooding

Type	Typical causes	Description
River flooding	Heavy rainfall and/or rapid snowmelt	High levels and flows in rivers, streams and creeks due to intense rainfall from localized events, such as thunderstorms, or as part of more widespread rainfall, perhaps exacerbated by blockages from debris (see Chap. 8)
Ice Jams	High river flows leading to ice break up, possibly associated with increased air temperatures	Out of bank flows due to the build-up of water when floating ice gets trapped by bridges, channel constrictions and other features, and the sudden release of water when ice jams break up (see Chap. 8)
Debris flows	Heavy rainfall and/or rapid snowmelt	Fast moving streams of mud, rocks and other debris generated by heavy rainfall, possibly exacerbated by the damage to vegetation caused by recent wildfires (see Chap. 9)
Urban flooding	Heavy rainfall and/or rapid snowmelt	Surface water or pluvial flooding which occurs when the drainage network cannot remove water sufficiently quickly, possibly exacerbated by a range of other factors, such as river flooding (see Chap. 10)
Dam break	High inflows, structural failure and/or landslides or debris flows into a reservoir	Overtopping or failure of dam walls leading to fast-moving, deep flows further downstream. Emergency flow releases or flows from self-priming siphons also present a risk at some reservoirs (see Chap. 11)
Outburst floods	As for dam break	Flash floods due to the failure or overtopping of naturally occurring barriers to flow, with much the same effect as a dam break; for example Glacial Lake Outburst Floods (see Chap. 11)
Levee breaches	High river levels and/or structural failures	Overtopping or failure of levees due to high river levels and/or structural issues leading to rapid inundation of previously defended areas (see Chap. 11)

type of flood from the slower responding events which occur on lowland rivers, for which alternative names include plains, riverine or fluvial flooding. Flash floods are sometimes also described as 'short-fuse' or 'rapid-onset' events, along with other types of fast developing natural hazards such as earthquakes, tornadoes and volcanic eruptions. Of course it is possible for several types of flooding to occur in a single rainfall event; for example, during tropical cyclones or the passage of a frontal system, flash floods often start in the higher parts of a watershed and are followed by riverine flooding further downstream. Surface water flooding is also often a risk in towns and cities.

Some well-known examples of flash floods include the Johnstown flood in Pennsylvania in 1889 and the Big Thompson Flood in Colorado in 1976. The first of these events occurred when a dam failed following prolonged heavy rainfall, resulting in the deaths of more than 2,000 people, whilst the second led to more than 140 fatalities following a thunderstorm in the headwaters of a steep mountain canyon. Table 1.2 provides more background on these and other well-known events and further examples are presented in later chapters. Chapter 4 also provides a brief introduction to the meteorological causes of flash flooding which, as well as thunderstorms, can include atmospheric rivers, cut-off lows, frontal systems, Mesoscale Convective Systems, monsoons, and tropical cyclones. Various combinations also occur, such as thunderstorms embedded in widespread frontal events, with orographic enhancement often intensifying rainfall in mountain regions.

For some countries, estimates are available for the long-term risk from flash flooding. For example, in the contiguous USA, an analysis for the period 1959 to 2005 (excluding Hurricane Katrina) suggested that there were typically about 100 flood-related fatalities per year (Ashley and Ashley 2008), with flash flood related deaths exceeding those from other types of flood. About 12% of events were attributable to dam or levee failures. For all types of flooding, approximately 63% of fatalities occurred in vehicles.

By contrast, in China, some estimates suggest that approximately two-thirds of flood-related casualties arise from flash floods, landslides and mud flows (Li 2006) whilst, in Europe, over the period 1998–2008, it has been estimated that there were more than 1,000 fatalities from all types of flood, including flash floods (EEA 2010). Again, for Europe, an analysis of major flood events from 1950 to 2006 (Barredo 2007) suggested that approximately 40% of fatalities arise from flash floods (about 50 per year).

More generally, an analysis of international data for the period 1975–2002 (Jonkman 2005) suggested that the mortality rate for flash floods (3.6%) is significantly higher than for other types of floods and is comparable to that for earthquakes and windstorms. For example, based on a 2007 international survey of National Meteorological and Hydrological Services (World Meteorological Organisation 2008), more than 100 countries were identified as affected by flash floods, which were considered second only to strong winds as a major hazard.

However, the question of whether the risk of flash flooding is increasing generally remains open, at least regarding the hydrometeorological aspects, although in many countries a range of other (anthropogenic) factors have increased the risk. These include:

- Increased settlement and recreational uses in mountain areas
- Encroachment of housing and infrastructure onto existing floodplains in lower-lying areas
- Development in urban areas affecting drainage paths and increasing the proportion of paved and other relatively impervious areas, exacerbated by a lack of maintenance in some cases

Table 1.2 Some examples of major flash flood events

Type	Location	Year	Description
River flooding	Gard region, southern France	2002	An extensive slow-moving mesoscale convective system deposited more than 600 mm of rainfall in 24 h resulting in 23 deaths and economic damages valued at about 1.5 billion dollars (Anquetin et al. 2009)
	Big Thompson Canyon, USA	1976	Approximately 300–350 mm of rainfall fell in 4–5 h due to a near-stationary thunderstorm. 144 people died and 418 homes and businesses were damaged, and many mobile homes, vehicles and bridges (Gruntfest 1996; USGS 2006)
Ice Jam	Montpelier, USA	1992	An ice jam formed at a bridge causing levels upstream to rise leading to extensive flooding in the city within one hour. Hundreds of residents were evacuated and 120 businesses disrupted in the subsequent flood (Abair et al. 1992)
Debris flow	Northern Venezuela	1999	14 days of heavy rainfall were followed by 900 mm of rainfall in 3 days. Thousands of people were killed in the resulting debris flows and many towns devastated along a 50 km section of the coastal zone (Lopez and Courtel 2008)
	Southern Taiwan	2009	A slow-moving typhoon (Morakot) with daily rainfall reaching 1,200 mm in some places, and some 4-day totals exceeding 3,000 mm, caused widespread flash flooding and debris flows resulting in more than 700 fatalities and losses of about $500 million (Chien and Kuo 2011)
Urban flooding	Texas, Louisiana, USA	2001	Flash flooding from heavy rainfall and thunderstorms associated with Tropical Storm Allison, with rainfall exceeding 250 mm in a few hours in the Houston area, resulted in 22 fatalities and flooding of more than 45,000 homes and businesses and 70,000 vehicles in Harris County with further impacts elsewhere (U.S. Department of Commerce 2001)
	Hull, UK	2007	Heavy sustained rainfall of about 110 mm in about 10 hours following weeks of wet weather caused flooding of approximately 8,600 homes and 1,300 businesses due primarily to the drainage system being overwhelmed (Coulthard et al. 2007)
Dam break	Johnstown, USA	1889	An unusually heavy storm crossed the region and continued into the following day, with the 24-h rainfall for the previous day estimated at 150–250 mm. Some 2,209 people perished and 27,000 were left homeless in the town of Johnstown when a dam failed (e.g. Frank 1988; see Box 11.1)
Levee breach	New Orleans, USA	2005	During Hurricane Katrina, which caused more than 1,000 fatalities, a significant proportion of the flood damages resulted from the failure of concrete floodwalls or overtopping and erosion of levees in more than 50 locations (ASCE 2007)
Outburst flood	Huaraz, Peru	1941	The moraine dam containing Lake Palca collapsed due to an icefall into the lake. There were more than 6,000 fatalities in the city of Huaraz located 22–23 km downstream (Lliboutry et al. 1977)

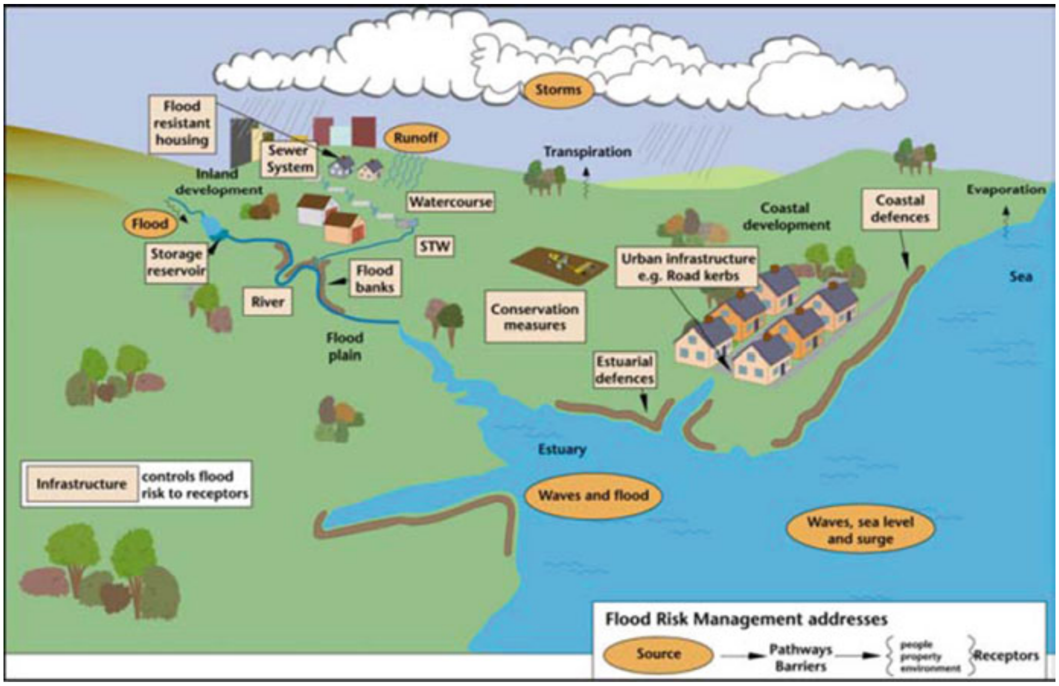

Fig. 1.1 A hydraulic perspective of the physical flooding system (Office of Science and Technology 2003)

- Widening ownership of cars and other vehicles with extensions of road networks into mountainous areas and coastal zones
- Catchment degradation, leading to increased sedimentation and reduced river channel carrying capacities and an increased risk of debris flows

For example, Fig. 1.1 illustrates some of the complex interactions which can occur in and around urban areas, where flooding mechanisms are often affected by a wide range of factors.

Estimates for the scale of the risk also depend on the definitions used for flash floods (Table 1.3). The classical view, popularized in films and books, is of a wall of water arriving unexpectedly under clear skies. Examples include the floods which occasionally occur in canyons in arid and semi-arid regions and events due to dam breaks. However, flash floods are often defined in terms of the times over which they develop following heavy rainfall, with values of 4–6 h widely quoted. For example, in a review of 16 definitions provided in scientific papers, guidelines and standards (Kobiyama and Goerl 2007), four mentioned a specific catchment response time (6 or 12 h), with some of the remainder mentioning ‘hours’ or citing factors such as catchment areas and the spatial and temporal scale of the precipitation. As discussed in later chapters, one particularly useful consideration is the scale of storms relative to typical catchment scales (e.g. Kelsch 2001).

An alternative approach is to define a flash flood as an event where there is insufficient time for an effective emergency response. In this case, the catchment response time is just one factor to consider, along with other issues such as public

Table 1.3 Some examples of approaches to defining flash floods

Reference	Definition
ACTIF (2004)	A flash flood can be defined as a flood that threatens damage at a critical location in the catchment, where the time for the development of the flood from the upstream catchment is less than the time needed to activate warning, flood defence or mitigation measures downstream of the critical location. Thus with current technology even when the event is forecast, the achievable lead-time is not sufficient to implement preventative measures (e.g. evacuation, erecting of flood barriers)
APFM (2006)	Flash floods occur as a result of the rapid accumulation and release of runoff waters from upstream mountainous areas, which can be caused by heavy rainfall, cloud bursts, landslides, the sudden break-up of an ice jam or failure of flood control works. They are characterized by a sharp rise followed by relatively rapid recession causing high flow velocities. Discharges quickly reach a maximum and diminish almost as rapidly. Flash floods are particularly common in mountainous areas and desert regions but are a potential threat in any area where the terrain is steep, surface runoff rates are high, streams flow in narrow canyons and severe thunderstorms prevail. They are more destructive than other types of flooding because of their unpredictable nature and unusually strong currents carrying large concentrations of sediment and debris, giving little or no time for communities living in its path to prepare for it and causing major destruction to infrastructures, humans and animals, rice and crop fields and whatever stands in their way
NOAA (2010)	A rapid and extreme flow of high water into a normally dry area, or a rapid water level rise in a stream or creek above a predetermined flood level, beginning within six hours of the causative event (e.g. intense rainfall, dam failure, ice jam). However, the actual time threshold may vary in different parts of the country. Ongoing flooding can intensify to flash flooding in cases where intense rainfall results in a rapid surge of rising flood waters (U.S. National Weather Service)
World Meteorological Organisation (2009)	Flash floods are rapidly rising flood waters that are the result of excessive rainfall or dam break events. Rain-induced flash floods are excessive water flow events that develop within a few hours – typically less than 6 h – of the causative rainfall event, usually in mountainous areas or in areas with extensive impervious surfaces such as urban areas. Although most of the flash floods observed are rain induced, breaks of natural or human-made dams can also cause the release of excessive volumes of stored water in a short period of time with catastrophic consequences downstream. Examples are the break of ice jams or temporary debris dams

awareness of the actions to take on receiving a flash flood warning and the readiness of civil protection authorities. However, as noted later, there are wide variations in the warning lead times ideally required and these can often be significantly reduced by adopting more streamlined procedures and improved technologies.

More generally Montz and Gruntfest (2002) suggest that flash floods have the following characteristics:

- they occur suddenly, with little lead time for warning
- they are fast-moving and generally violent, resulting in a high threat to life and severe damage to property and infrastructure
- they are generally small in scale with regard to area of impact
- they are frequently associated with other events, such as riverine floods on larger streams and mudslides
- they are rare (Gruntfest and Handmer 2001)

Given these various approaches to defining flash floods, the precise definition is left open here and instead the focus is on the underlying techniques and procedures which are typically used in forecasting and warning systems. These often form part of a wider process of flood risk management and the following section provides a brief introduction to this topic. Later sections and chapters then discuss the main approaches which are used operationally, including monitoring and forecasting systems (Chaps. 2–5), warning dissemination techniques (Chap. 6) and longer-term planning (or 'preparedness') activities (Chap. 7). Chapters 8–11 then discuss the methods used for specific types of flash flooding, including river flooding, ice jams, debris flows, urban flooding, dam and levee breaks and glacial lake outburst floods. Finally, Chap. 12 concludes with a discussion of some current research themes in this rapidly-developing area.

1.2 Flood Risk Management

The concept of risk management runs through much current thinking on how best to deal with natural hazards and – for flooding – is a well-established approach. Flood risk is usually defined as the combination of the probability of flooding and the consequences; for example expressed in terms of the number of properties affected or the economic damages.

Other factors such as the age, health and mobility of individuals are increasingly considered and are particularly relevant to emergency planning for flash floods. For example, special arrangements may need to be made to evacuate people from care homes and hospitals if flooding is a possibility, taking account of the limited time likely to be available. This component of the overall risk is usually called the vulnerability and – as discussed in Chap. 7 – typically relates to more than just socioeconomic factors; for example, in a flash flood, some other vulnerable groups potentially include vehicle drivers and people who live in basement apartments.

One definition of vulnerability (UN/ISDR 2009) is therefore that it is "The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard". This typically includes a range of physical, social, economic, and environmental factors for which examples include "poor design and construction of buildings, inadequate protection of assets, lack of public

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

information and awareness, limited official recognition of risks and preparedness measures, and disregard for wise environmental management". Issues such as the legal environment and the impact of flooding on livelihoods may also need to be considered, and Table 1.4 compares how disaster reduction capacities often vary between richer and poorer countries.

Taken together these various factors all influence the design of flood forecasting and warning systems, and later chapters provide an introduction to some of the risk-based, cost-benefit, multi-criteria and other approaches used to guide the pace of development.

The approaches used to assess flash flood risk vary widely and are discussed in Chaps. 8–11 for individual applications such as river flooding and debris flows. Examples include hydrological and hydrodynamic modelling, reconstruction of flood outlines based on historical records, and multiple regression approaches linking flood magnitudes to soil types, slope and other factors. Geographic Information System (GIS) tools are often used in these types of analyses to produce maps of locations at risk and several examples are presented in later sections and chapters (see Box 1.2 for example). Some typical applications include flood zoning, insurance risk assessments and contingency planning. Flood warning and evacuation maps are also widely used by emergency managers during flood events; for example, showing additional information such as safe access and escape routes, shelter locations, medical facilities, and critical infrastructure such as water treatment works and power stations. Again examples are shown in later chapters.

Having identified the risk, possible mitigation measures then typically include 'steps to reduce the probability, the damage, or both' (Floodsite 2005) and to 'control, reduce or transfer the risk' (e.g. UN/ISDR 2009). For example, some options for reducing flood risk include structural measures such as the construction of levees and debris retention structures, and non-structural measures such as insurance incentives, revised planning policies, managed retreat, and improved building development codes.

Flood warning is another type of non-structural measure and is often visualised as part of a disaster risk management cycle as shown by the example in Fig. 1.2. This illustrates a cycle of continuing improvement in which the lessons learned from each

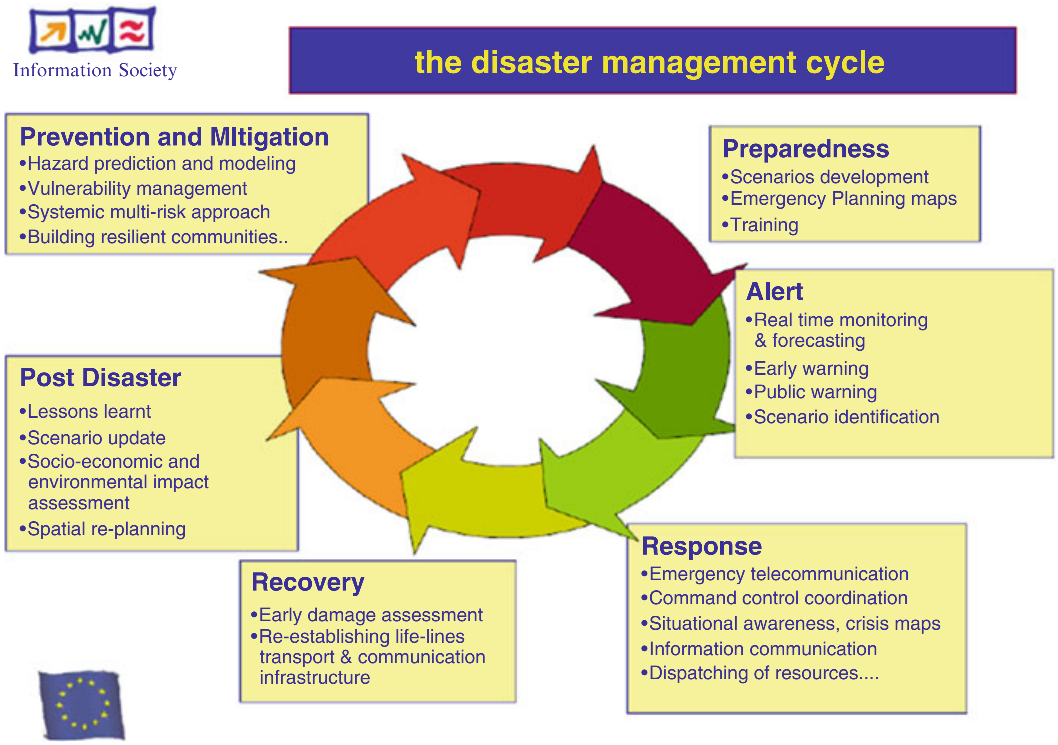

Fig. 1.2 The Disaster Management Cycle (© European Union, Information and Communication Technologies 2006; CORDIS, http://cordis.europa.eu/)

disaster feed into improvement plans which if possible should be implemented before the next event. In particular, performance monitoring techniques play an increasingly important role in helping to understand and improve the effectiveness of flood warning systems, as discussed in Chaps. 5 and 7 and illustrated in Box 1.2.

Compared to other types of floods, warning systems perhaps play a more important role for flash floods (e.g. Creutin et al. 2009). This is partly because – at least for river floods and debris flows – events tend to occur in less densely populated areas which, in some cases, have no recent history of flooding. It is therefore sometimes more difficult to justify significant investments in flood defences (levees) and other structural measures. More generally, even with structural measures in place, some residual risk remains since schemes are usually designed to achieve a particular standard of protection, such as a 1 in 100 year return period or 1% annual exceedance probability. Flood warning systems are therefore sometimes installed or retained even after construction to help to mitigate this risk, although of course even the best systems cannot eliminate the risk entirely.

1.3 Flash Flood Warning Systems

The main role of a flood warning system is usually to provide people and organisations with more time to prepare for flooding, thereby reducing the risk to life and the damage caused. Some typical emergency response actions include evacuation

Fig. 1.3 *Clockwise from top left*: temporary barriers on display at an exhibition of flood emergency response equipment (UK), flood closure gate in a levee system (USA), flood resilient temporary grain store as part of a community-based flood warning system (Malawi)

(organized, self-help), moving valuable items, and flood fighting and operational actions to reduce the extent of flooding (e.g. Fig. 1.3). For example, in a post event survey of flooding in parts of the Elbe and Danube catchments (Thieken et al. 2007), the emergency measures reported by residents included: put moveable contents upstairs; drive vehicles to a flood-safe place; safeguard documents and valuables; protect the building against inflowing water; switch off gas/electricity; disconnect household appliances/white goods; gas/electricity was switched off by public services; protect oil tanks; install water pumps; seal drainage/prevent backwater; safeguard domestic animals/pets; redirect water flow.

As with most other types of natural hazard, the operation of a flash flood warning system typically involves the following steps:

- Monitoring – near real-time observations of the conditions likely to cause the hazard
- Forecasting – the use of computer or paper-based models to estimate the likely timing, location and magnitude of the event, based on the observations available
- Warning – taking the decision to issue a warning, based on all of the information available, and then issuing it using a range of direct and indirect techniques

Typically conditions such as rainfall and river levels are monitored to assess the risk of flooding and – if appropriate – warnings are then sent to those likely to be affected. The outputs from flood forecasting models are also increasingly used as part of the decision-making process, and can potentially help to extend the lead time provided. The approaches used for dissemination or notification of warnings vary widely but include telephones (landline/cell), sirens, door-knocking and loud-hailers as well as a range of indirect methods, such as television, radio and the internet.

As a flood develops, messages are typically escalated from an initial alert or watch through to a flood warning. In meteorology this is sometimes referred to as a 'Ready-Set-Go' approach, in which the severity of warnings is increased as the confidence in forecasts increases. For example, the following four hydrologic product categories might be used (NOAA 2010):

- The hydrologic outlook ("Ready") – used to indicate that a hazardous flooding event may develop. It is intended to provide information to those who need considerable lead time (days) to prepare for an event. It is generally issued as a plain language narrative
- The flash flood watch ("Set") – used when the expectation of a flood event has increased, but its occurrence, location, and/or timing is still uncertain. It is intended to provide enough lead time (hours) so those who need to set their mitigation plans in motion can do so
- Flash flood warnings ("Go") – issued without regard to time frame, whenever an event is occurring, imminent, or has a very high probability of occurrence
- Flash flood statements – various advisories and update information issued as needed to cancel, expire, extend, or continue a Flash flood warning

However, as discussed in Chap. 6, the messages used vary widely between countries and are often associated with visual alerts, such as colour codes (e.g. yellow, amber, red), and keywords indicating the expected severity of flooding (e.g. minor, moderate, major).

Between flood events, most flood warning services have ongoing programmes to improve systems and procedures; that is, the level of 'preparedness'. In particular, community involvement is usually emphasized as crucial to the success of a system and this is often termed a people-centred, integrated or end-to-end approach, or total warning system (e.g. Hall 1981; Basher 2006; Australian Government 2009; UN/ISDR 2006; World Meteorological Organisation 2006a). Table 1.5 summarises some of the typical tasks and components required with this type of approach and these are discussed in more detail in later chapters. Box 1.1 also describes a long-established catchment-wide flood forecasting and warning system which illustrates many of these principles.

Some aspects of the emergency response are also discussed briefly in later sections, since the times required often need to be factored into the choice of monitoring, forecasting and warning techniques. For example, this might include how long it typically takes people to leave areas at risk or to move property and valuables to safer locations, and the time needed for a more widespread evacuation if a severe flood seems to be developing. Other examples could include estimates for the times

Table 1.5 Some key features of many flash flood warning systems

Item	Description/options
Monitoring	Telemetered or manual observations using raingauges, weather radar, river level and flow gauges and – where appropriate – satellite observations and other types of instrumentation such as reservoir and lake level gauges. Sometimes called detection, data acquisition or data collection (see Chaps. 2, 3, and 12, and Chaps. 8–11 for specific types of flash flood)
Forecasting	Rainfall forecasting using atmospheric models and simpler nowcasting techniques, and flood forecasting using rainfall-runoff (hydrologic) models, and possibly flow routing (hydrological or hydrodynamic) models. Sometimes called prediction (see Chaps. 4, 5, and 12, and Chaps. 8–11 for specific types of flash flood)
Warning	Taking the decision to issue warnings, possibly with the assistance of decision-support systems, and then disseminating warnings to communities, civil protection authorities, the emergency services and others using a range of direct, community-based and indirect techniques. Sometimes called message construction and communication, notification, warning communication or flood threat recognition (see Chaps. 6 and 12, and Chaps. 8–11 for specific types of flash flood)
Preparedness	Post-event reviews, performance monitoring and reporting, flood risk assessment, preparing flood response plans, interagency coordination, organizing tabletop and full-scale flood response exercises, running public awareness campaigns, holding community meetings and consultations, developing and improving monitoring, forecasting and warning systems, extending the flood warning service to new locations, and a range of other activities (see Chap. 7)

that would be required for flood fighting actions such as reinforcing levees or to collect and then place sandbags at individual properties.

Of course, the actual response times required vary widely between individuals and organisations and usually need to be estimated on a case-by-case basis. For example, in some cases, just a few minutes could be required for villagers, campsite residents or hikers to move to higher ground, but several hours or more to install demountable defences or draw down a reservoir to provide additional flood storage. Other factors are sometimes relevant such as the time of day or night and past experience of flooding, with perhaps one of the most challenging situations being a large-scale evacuation of a residential area, at night, in winter, with many roads closed due to floodwater. Some organisations also include targets for minimum warning lead times in their strategic plans or service level agreements.

Potential loss-of-life studies for dam breaks also show that it is sometimes possible to save significant numbers of lives even with very short lead times. For example, based on evidence from a number of events, one study suggested that the loss of life could be reduced to below 1% with more than 90 min of warning (Brown and Graham 1988). Similarly, for another fast response or 'short-fuse' type of natural hazard – tornadoes – a survey of 62 emergency managers in Oklahoma suggested that the median ideal warning time was 23 min, and the times quoted were all in the range

10–120 min (League et al. 2010). However, emergency response procedures generally need to be well defined and rehearsed to make use of times as short as these. Also, the most appropriate types of response often vary between types of flash flood. For example, for dam breaks and – to a lesser extent – debris flows the focus is often on evacuation, whilst for river and surface water flooding other options may be available, such as moving to higher floors in a building and using sandbags and other temporary measures to reduce the impacts of flooding.

More generally, as might be expected, many studies have shown that the economic losses to property and vehicles are normally reduced by providing more lead time, and this topic is discussed further in Chap. 7. The effectiveness of warnings can also be improved through public awareness campaigns and emergency response exercises, thereby providing residents and emergency responders with a better understanding of the actions to take on receipt of a warning. For example, as discussed in Chap. 6, in addition to being accurate, a forecast or warning needs to be clear and understandable, available to all, reliable and timely, authoritative, and collaborative (World Meteorological Organisation World Meteorological 2006a). These social response factors are therefore an important consideration in the design and operation of any warning system and shortfalls in this area often lead to systems not reaching their full potential (e.g. Gruntfest 1993; Handmer 2002; Parker 2003; Australian Government 2009; Parker and Priest 2012).

Box 1.1 Susquehanna Flood Forecast and Warning System, USA

The Susquehanna River originates at Lake Otsego in Cooperstown, New York State and flows 708 km to the Chesapeake Bay in Maryland. The catchment has an area of 70,400 km^2 and is divided into six sub-basins which include the Upper Susquehanna, Chemung, Middle Susquehanna, West Branch Susquehanna, Juniata and Lower Susquehanna. Major tributaries include the Chemung, Juniata and Lower Susquehanna.

The basin is generally recognised as one of the most flood-prone in the USA with more than 80% of the 1,400 municipalities having some areas at risk from flooding. This includes communities such as Binghamton New York, Wilkes-Barre Pennsylvania and Harrisburg Pennsylvania. Notable flood events have included Tropical Storm Agnes in 1972, snowmelt and ice jam events in 1996, Tropical Storm Ivan in 2004, the summer storms of 2006, and Tropical Storms Irene and Lee in 2011. In a major event, a typical scenario is for flash flooding on the smaller creeks and tributaries to develop into slower responding riverine flooding at locations further downstream in the basin.

The Susquehanna Flood Forecast and Warning System (SSFWS) was established in 1986 as a partnership of the Susquehanna River Basin

(continued)

Box 1.1 (continued)

Commission (SRBC), the National Weather Service (NWS), the U.S. Army Corps of Engineers (USACE), and the U.S. Geological Survey (USGS). Other partner organisations include the Pennsylvania Department of Community and Economic Development and the environmental and emergency management agencies of New York State, Pennsylvania and Maryland (Fig. 1.4). The following program goals were established (SRBC 2011):

- Develop a sustainable, state-of-the-art observational network
- Provide as much lead-time and accuracy in forecasts and warnings as practicably possible
- Evaluate the spatial distribution of flood damages in the basin
- Expand the flood warning system to support water resources management of public water supply, drought, and recreation within the basin
- Improve flood warning dissemination through the use of technology
- Increase public awareness, support, and use of National Weather Service products
- Develop a mechanism for administration and secure source of funding for the SFFWS

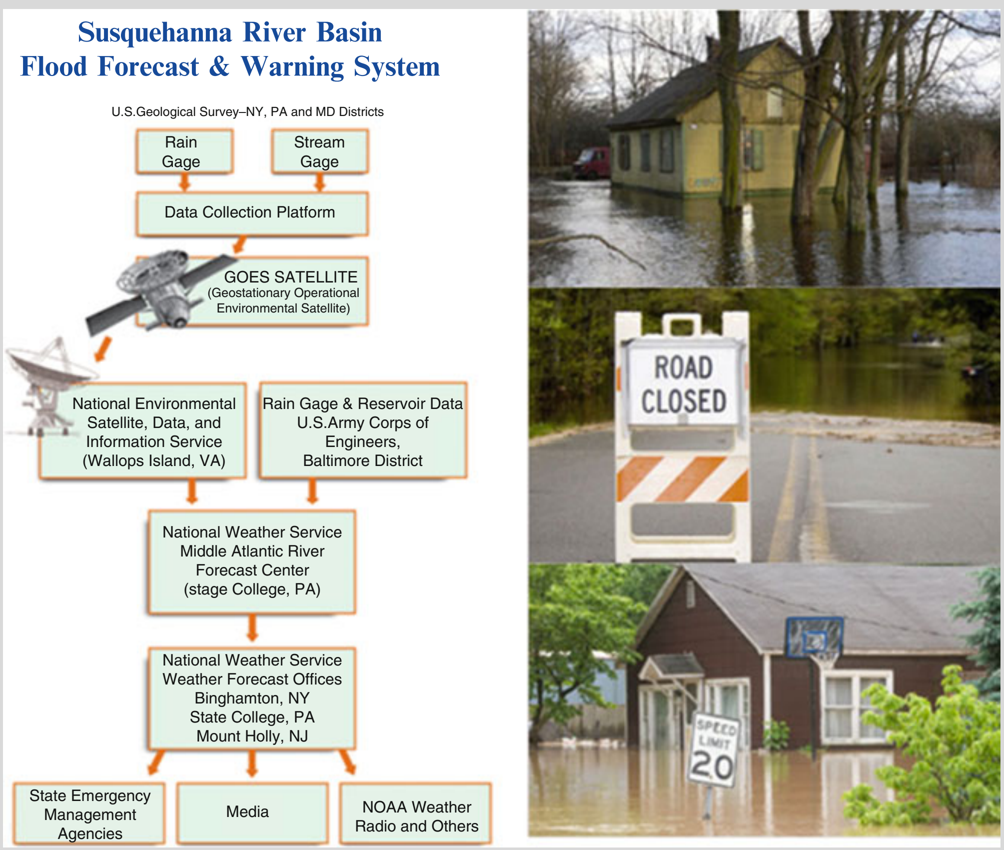

Fig. 1.4 Schematic of the Susquehanna Flood Forecast and Warning System (SRBC 2011) and images from the system website http://www.susquehannafloodforecasting.org/

(continued)

Box 1.1 (continued)

This has included the installation of more than 70 raingauges and 60 river gauges and 91 Data Collection Platforms. The Data Collection Platforms provide high rate data transfer using satellite telemetry with landline telephone links as a backup. Other activities have included the production of stage inundation maps that relate expected area and depth of flooding in a community to stage at a local stream gauge, installation of 'Turn Around; Don't Drown' signs on highways at risk from flooding, and a wide range of awareness-raising and community engagement initiatives. In recent years, as forecasting and warning technologies have improved, a key aim has also been to extend the service to include faster response flash flood prone tributaries within the basin.

The system is estimated to reduce flood damages by an average of $32 million per year (SRBC 2011); for example, post-event analysis of the June 1996 flash floods suggested that early warnings saved lives and an estimated $100 million in property damage, including the following actions:

- Wilkes-Barre, PA, got 6 h warning, allowing 110,000 people to evacuate.
- Harrisburg got 4 h warning, giving officials time to implement emergency management measures.
- U.S. Army Corps of Engineers dams held back 167 billion gallons of flood water, averting another $1.3 billion in damages

River level forecasts and flash flood guidance are issued by the Middle Atlantic River Forecast Center of the National Weather Service and the Binghamton, NY and State College, PA Weather Forecast Offices (Fig. 1.5). River forecasts are based on river level, reservoir, lake, raingauge and weather radar observations, multi-sensor precipitation estimates, air temperatures, rainfall forecasts, and a range of other information, such as data provided by river ice observers during the winter months. From 2011, the forecasts also include an ensemble component based on multiple rainfall forecast scenarios generated from different atmospheric models. The following flood severity categories are defined based on the anticipated threat to people and property:

- Minor Flooding: Minimal or no property damage, but possibly some public threat or inconvenience
- Moderate Flooding: Some inundation of structures and roads near streams. Some evacuations of people and/or transfer of property to higher elevations are necessary
- Major Flooding: Extensive inundation of structures and roads. Significant evacuations of people and/or transfer of property to higher elevations

Warnings are issued to state emergency management agencies, other government bodies, and the general public through news media. The state agencies then inform county authorities who in turn alert local emergency management officials and others who require warnings.

(continued)

Box 1.1 (continued)

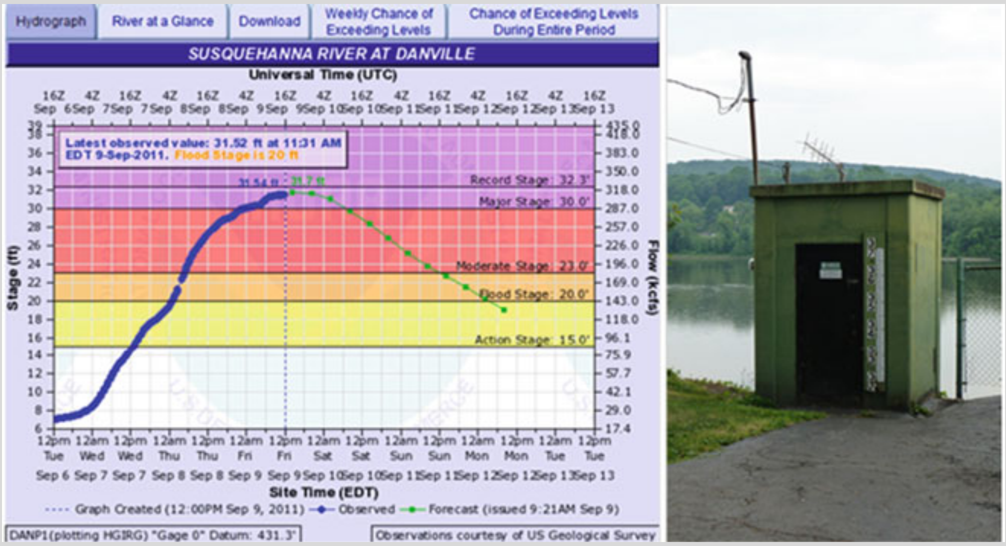

Fig. 1.5 Example of river stage observations and forecasts and flood warning threshold values for the Danville gauge (National Weather Service: http://water.weather.gov/ahps2/). The graph is from the floods during September 2011 whilst the photograph shows the river and the gauge kiosk under more normal flow conditions

To assist in the interpretation of warnings, an internet based mapping tool is also available called the Susquehanna Inundation Mapping Viewer (SIMV) (http://maps.srbc.net/). The online map viewer displays inundation extents and expected depths relative to local USGS river gauge levels using a Google Maps ® interface. The system has been designed for use by the public and emergency managers to assess the likely severity of flooding based on river level observations and forecasts (Pratt et al. 2010). The viewer supplements the original approach which SRBC pioneered in the 1970s in which paper-based 'flood stage forecast maps' were distributed to communities in the basin. Other developments include extending the flood warning service to smaller tributaries, making more use of rainfall forecasts, widening use of the system for water resources and drought forecasting applications, and improved techniques for the dissemination of warnings.

1.4 Organisational Issues

There are many possible ways to organise a flood warning service. For example, a 1991 survey of 67 countries (reported in World Meteorological Organisation 2001, 2009) found four principal models for the organization of national hydrological or

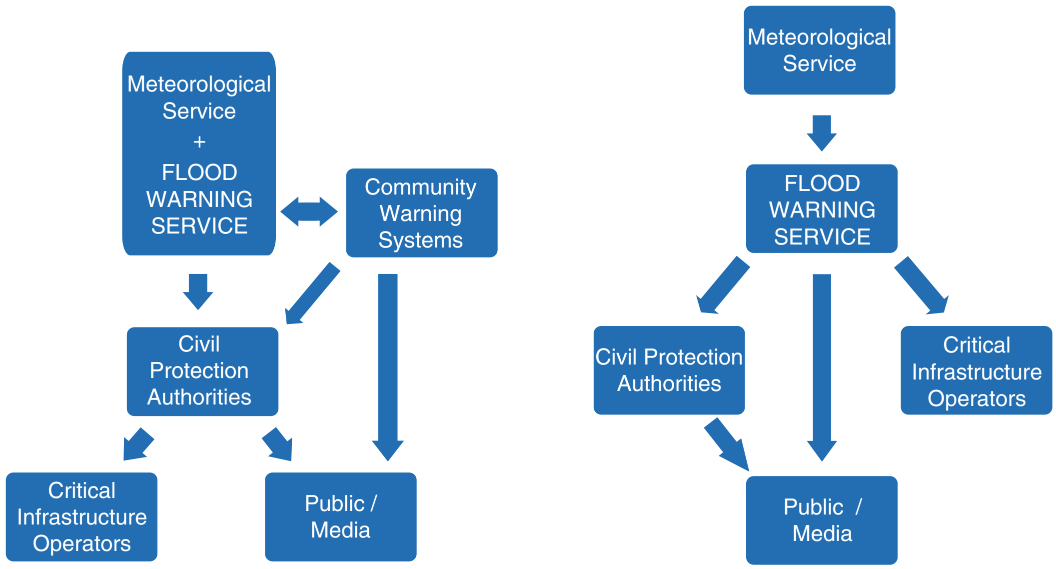

Fig. 1.6 Illustration of two possible approaches to the organization of a national flood warning service; here the term civil protection authority includes local government and emergency responders. The *arrows* indicate responsibilities for the dissemination / notification of heavy rainfall and flood warnings (note that community representatives may also alert critical infrastructure operators directly)

hydrometeorological agencies: national (51%), regional or subnational (1%), both national and regional (42%), and neither national or regional (6%). A 2007 survey (World Meteorological Organisation 2008) also showed that the meteorological and hydrological services were combined in less than half of 139 responding countries. In many cases the requirement was noted for nationally accepted 'readiness levels' requiring specific actions on receipt of a warning and – where services were separate – strengthened coordination and collaboration, particularly for issuing hazard warnings.

More generally, Fig. 1.6 illustrates two common options which are used for issuing flood warnings, consisting of a combined national and community-based approach and a fully centralized system. For example, one common choice is for a national centre – often via a network of regional offices – to provide warnings for major rivers, with community-based systems operated on smaller rivers and streams at risk from flash flooding (e.g. Box 1.2).

Depending on the country, flood warning services are typically operated by national hydrological services, environmental regulators, river management agencies, or civil protection authorities (see Chap. 6). In some cases, warnings are issued directly to all those likely to be affected, or instead through an intermediary such as the emergency services. Some flood warning services also have responsibilities for assisting in the emergency response, such as with evacuating properties, flood fighting and helping to protect critical assets. These activities are often performed by regional or local offices, with the national centre providing longer-range forecasts and technical and strategic support. By contrast, in the community-based approach, most activities are performed locally and some essential elements can include (Hall 1981):

- Volunteer rainfall and stream gauge observers
- A reliable and rapid local communication system with emergency backup
- A flash flood warning coordinator and alternative
- Forecast procedures
- A warning dissemination plan
- An adequate preparedness plan (including public education)

However, there is often close collaboration with national and regional centres; for example with community-based observers reporting 'on-the-ground' information to help with regional flood forecasting, and meteorological and hydrological services providing rainfall forecasts, flood forecasts for larger rivers, and technical support when setting up and running schemes (e.g. USACE 1996; FEMA 2006; NOAA/NWS 2010).

For flash floods, the rapid response of flows to rainfall usually also requires close collaboration between meteorological and hydrological services, if these are separate. For example, some organisations have hydrometeorologist posts for people skilled in both disciplines or operate joint forecasting centres. Information from flood patrols, emergency response teams, volunteer observers and others on site is also particularly useful during flash floods to provide up-to-date information on flooding conditions. In some countries (see Chap. 6), this flow of information is formally integrated into warning systems to assist in the decision-making process. For example, in Switzerland a common information platform is operated for natural hazards, which for flash floods includes observations, forecasts and descriptive feedback from observers (Heil et al. 2010; Romang et al. 2011). Similarly, in the USA, a network of trained volunteer 'spotters' reports information on flash floods, tornadoes and other fast developing hazards, and includes some 300,000 participants (http://www.skywarn.org/).

In some flood warning services, the warnings issued are mainly advisory (e.g. 'There is a high risk of flooding in your area') but in some cases are prescriptive (e.g. 'Leave your property now!'). In the latter case, there is then the question of the authority to enforce any instructions which are provided. Some types of flooding may also be excluded from the service provided due to the technical difficulties involved, cost or lack of any legal requirement to provide warnings. Typical examples include the flooding from surface water in urban areas or from ice jams, although most organisations try to provide at least a basic service if possible where there is a significant risk. These issues, and the overall objectives of the service, are often summarized in an overall strategic plan or concept of operations agreed with all other agencies involved in the emergency response process and key community members. For example, World Meteorological Organisation (2011) notes that "It is now recognized that the importance of flood forecasting and warning as a process in managing flood risk and impacts requires a full-time and structured organizational approach. It is no longer something that can be added on as a temporary contingency operation within an organization fulfilling other primary roles, for example public works or municipalities."

Regarding the authority and powers of the various organisations involved in issuing and responding to warnings, the approaches used vary widely. In some countries, in recent years there have also been significant updates to the legislation surrounding disaster response. For example, some changes which have significantly improved the overall approaches used for floods and other disasters have included loi Risques n°2003-699 on risk prevention in France (2003), and the Water Resources Act (1991), Environment Act (1995) and Civil Contingencies Act (2004) in the UK. For flash floods in particular, one important consideration is that there is often only a limited amount of time available for consultation and requesting permissions, perhaps requiring a higher level of decision-making authority and preparedness at local and regional level than for some other types of natural hazard.

In addition to changes to legislation, in many countries a typical progression in developing a flood warning service has been to start with a river monitoring-based service, using observations relayed by observers or telemetry. This has then progressed to make use of rainfall observations and forecasts in the process and – in many cases – computer-based flood forecasting models. Other types of flooding might also start to be considered (e.g. debris flows). Another key step is often deciding to move from offering a service on a 'best-endeavours' basis to operating 'round-the-clock' (24/7) during flood events (i.e. 24 hours per day/7 days per week, or 24/7). Other changes typically include the introduction of a long-term strategy for flood warning and forecasting accompanied by service level agreements and routine performance monitoring and post-event reporting. However, even in the most sophisticated systems, informal and indigenous approaches still have a valuable role to play (e.g. Handmer 2001; Australian Government 2009), particularly when integrated into more formal systems. For example, some benefits of an informal approach can include (Parker 2003):

- Amplifies formal warnings extending warning penetration in the community
- Increases the quality and specificity of information received, reinforcing formal warning
- Gives greater local credibility to warnings, and may address emotional or affective need
- Translates warning messages into the vernacular
- Delivers warning as a dialogue reducing the need for confirmation

The issue of resilience is also important and backup or contingency procedures normally need to be included for all key components, including telemetry, forecasting and warning dissemination systems. For example, some organisations keep simpler paper-based approaches available in case of problems with real-time forecasting systems and as a 'reality-check' on model outputs. Other considerations include the need for backup power supplies and communication routes and – in some cases – whether to use dual-path telemetry and back up instruments at high risk locations. In some flood warning services a backup operations centre is maintained in case of flooding or other problems with the main site, with written procedures for switching operations from one location to the other.

Another option is to use a fully automated warning system in which an alert is issued whenever critical thresholds are exceeded at gauge sites, typically using approaches such as sirens or alarm bells (see Chap. 6). However due to the uncertainties involved, and the possibility of power, gauge and other failures, these types of systems tend to be used less frequently, and not at all in some countries, since generally the view is that some expert review and interpretation is needed before a warning is issued. However, this approach is sometimes useful where the consequences of false alarms or equipment malfunctions can be tolerated, such as with the use of flashing lights and automatic barriers at low water crossings on roads (see Chap. 12). Also, in very fast developing events, such as dam breaks, an automated system is sometimes the only technical option for providing warnings in time to those residents living close to the dam site (see Chap. 11). Another recent development in some countries has been to provide a website facility to allow members of the public to define rainfall and/or river level thresholds for receiving alerts by text message, email or synthetic voice message (e.g. Box 3.1 and Chap. 4). However, this is generally on an information-only basis and the onus is on the recipient to take decisions regarding the most appropriate action to take.

Box 1.2 Binahaan River Local Flood Early Warning System, the Philippines

The Philippines archipelago includes more than 7,000 islands and Leyte is one of the largest. It lies within the eastern part of the Visayas group of islands. The province of Leyte has a population of approximately 1.7 million people in an area of 5,700 km^2 (http://www.leyte.org.ph/).

The terrain is generally mountainous and floods, landslides and debris flows present a considerable hazard, particularly during the typhoon season. Leyte is mainly located in the Type IV climate zone of the Philippines in which rainfall is more or less equally distributed throughout the year (http://www.pagasa.dost.gov.ph/).

The Binahaan catchment is in the northeast of Leyte. It has an area of 272 km^2 and the maximum elevation is approximately 1,330 m above sea level. There are estimated to be at least 20,000 people in 4,000 households at risk from flooding (Provincial Planning and Development Office 2009). The main risks are to agricultural produce, livestock, houses and other properties, and damage-causing floods occur every year.

This catchment was the location for the first telemetry-based community flood warning system to be established in the Philippines (Neussner 2009; Neussner et al. 2009; Kerle and Neussner 2010). The system was established in 2007 and was developed by the Province of Leyte in collaboration with the German Development Cooperation agency (GIZ). It forms part of a network of community based flood warning systems which until that time had relied mainly on manual observations of rainfall and river levels (Hernando 2007, 2008).

(continued)

Box 1.2 (continued)

These complement the flood forecasting and warning service offered on larger rivers such as the Pampanga by the Pampanga River Basin Flood Forecasting and Warning Centre (PRBFFWC). This centre is part of the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) which also provided technical assistance in developing the hydrological aspects of the system.

The Operations Centre is located in the town of Palo near the lower reaches of the catchment and is staffed year-round, 24 h a day. Real-time information is received by radio telemetry from a tipping bucket raingauge and a pressure transducer water level sensor in the upper reaches of the catchment and an automatic weather station based in the Operations Centre. Cell-phone (GSM) data transmission was used initially although later replaced by VHF/UHF telemetry to improve reliability. The network also includes 4 manually-read raingauges and 3 river level staff gauges; observations at these sites are made by volunteer observers twice-daily and more frequently during heavy rainfall events, and are sent to the operations centre using text messages (SMS) or hand-held radio. Weather forecasts and typhoon and tropical storm warnings are also received from PAGASA and other sources. A standby generator is available in case of problems with power supplies to the computer, telemetry or communications equipment.

As river levels rise, observations are compared to pre-defined alert and threshold values and, if these are exceeded, warnings are issued to municipal and community disaster coordinating councils, the Department of Education and the provincial radio station. An initial alert is also provided if the observed rainfall exceeds 20 mm in 3 h. In addition to land line and mobile phones, hand-held radios are widely used for communications during flood events; for example to relay observations of flooding of roads and properties to the operations centre. They are also sometimes more reliable during heavy rainfall. At community level, the methods used to disseminate warnings include bells, motorcycle messengers and handheld megaphones. Volunteer search and rescue teams can also be mobilised and are equipped to perform boat rescues.

A three stage warning system is used in which the alert levels used consist of Level 1-Standby, Level 2-Preparatory and Level 3-Evacuation. For example, for a Level 2 alert, in addition to hourly reporting, community-level actions include:

- Taking children, the elderly and disabled to evacuation areas
- Securing premises for a possible evacuation
- Securing or collecting water-vulnerable items, hardware, farm implements etc.
- Setting up lights, water, toilets, beds, blankets, medicine etc. for evacuation centres

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Box 1.2 (continued)

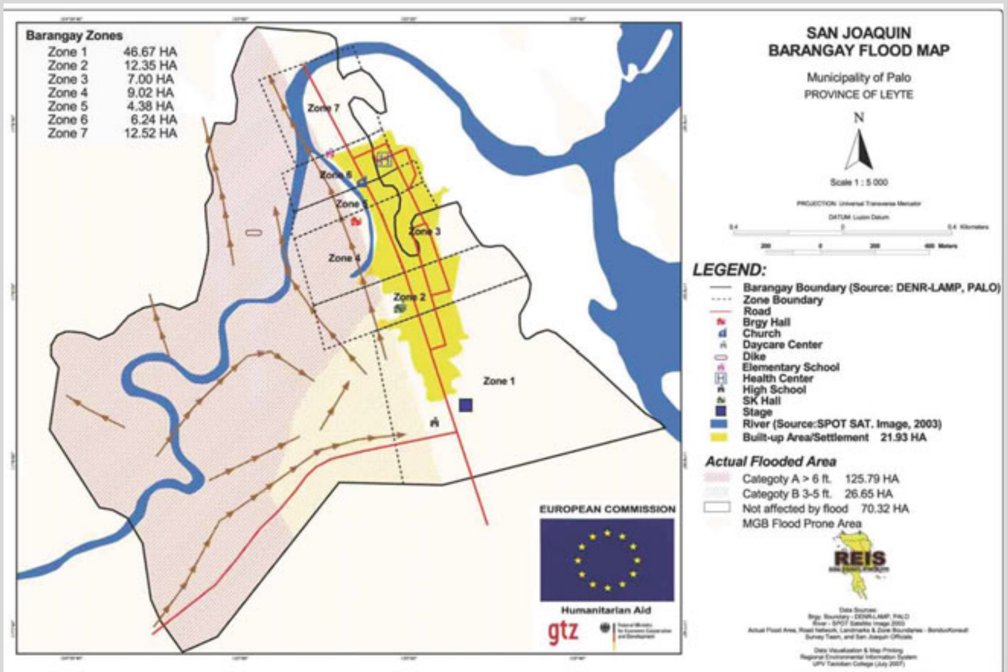

Fig. 1.7 A flood map for San Joaquin barangay, showing the areas at risk, likely flood depths and flood routes, and the community facilities and infrastructure at risk (German Development Cooperation agency; Provincial Government of Leyte, http://www.leyte.org.ph/binahaan/)

Food stores, livestock, household electronics, furniture and vehicles can also be moved if time permits. Evacuation centres are typically established in schools, churches and other community centres but, in emergencies, areas of high ground and bridges are sometimes used. The emergency response actions to be taken are documented in municipal and community (Barangay) Disaster Preparedness Plans which include flood maps for the areas at risk (e.g. Fig. 1.7).

To help with assessing the performance of the system, annual reports are issued covering topics such as flooding incidents which occurred, warnings issued, community education activities, improvements made, recommendations for future improvements, and performance statistics for the system. For example, following the first full year of operation, records showed that five Level 3 alerts were issued, with no false alarms (Provincial Planning and Development Office 2009). Based on this experience, some thresholds levels were subsequently refined to provide a longer lead time for warnings. Considering the period to 2010, the system was activated 13 times, giving residents between 3 and 10 h to move possessions and for evacuation to safe locations (Kerle and Neussner 2010).

(continued)

Box 1.2 (continued)

As part of the operation of the system, there is also an active programme of community engagement, which includes a training programme for observers, regular flood warning exercises (drills and dry runs), post event reviews and meetings, and seminars on disaster preparedness, management and contingency planning. The development of a flood forecasting capability is also planned to extend warning lead times. The general approach used has also been extended to other catchments in the Philippines.

1.5 Technological Developments

Since the earliest days of telegraphy and weather forecasting in the mid- to late-19th century, technological developments have helped to improve the methods used to observe and predict floods and to issue warnings to the public. Table 1.6 summarises some of the key developments which have played, or continue to play, an important role in this process.

These various developments, amongst others, have contributed to significant improvements in both the accuracy of flood warnings and the warning lead times provided. In particular, the time required for monitoring, forecasting and warning can sometimes be reduced considerably by adopting new procedures and techniques, as illustrated by the simple example in Fig. 1.8. However, as discussed earlier, the lead time required for an effective response depends on many social and operational factors and so needs to be considered separately for each situation.

Another option is to make greater use of rainfall forecasts to help to extend the time available. Figure 1.9 illustrates how rainfall forecasts are used in the river flood warning process. The meteorological inputs shown are specific to the UK and – in some cases – are now superseded and, as noted previously, flood warning codes vary widely between countries. However, the underlying techniques are often the same and usually consist of a combination of global and regional or local Numerical Weather Prediction (NWP) models for Quantitative Precipitation Forecasts (QPF) and a nowcasting approach – called Nimrod in this example – based on weather radar observations, NWP model outputs, and other types of real-time observations (see Chap. 4).

When using rainfall forecasts, typically this introduces more uncertainty into the warning process, particularly at longer lead times. However, the additional time provided is often useful to civil protection authorities, the emergency services and others for early mobilization of staff and precautionary actions, such as checking and deploying equipment. In some situations, even a few minutes of additional warning is valuable, although forecasts usually provide useful information for considerably longer periods than this.

Table 1.6 Some significant technological milestones relevant to flash flood warning (adapted from Sene 2010)

Period	General area	Description
1850–1900	Monitoring	First routine telegraphy of river levels and meteorological observations
	Meteorology	First public weather services (e.g. US Army Signal Corp, UK Met Office)
	Hydrology	Rational method for peak runoff estimation (Mulvaney)
	Hydrology	St Venant hydrodynamic equations (St Venant)
1900–1929	Meteorology	Principles of Numerical Weather Prediction (NWP) (Bjerknes)
	Meteorology	Manual trials of the NWP approach (Richardson)
	Hydrology	River flood forecasting service established (US Weather Bureau)
	Warning	First public weather forecasts by radio and teletype introduced
1930s	Hydrology	Unit Hydrograph rainfall-runoff modelling approach (Sherman)
	Hydrology	Muskingum flow routing approach (Muskingum)
	Warning	First experimental television public broadcasting services
1940s	Monitoring	Initial weather radar trials based on converted military radars
	Monitoring	Storm 'spotter' networks started in the USA
	Meteorology	Trials of data assimilation in NWP (Panofsky)
	Hydrology	Penman evaporation equation (Penman)
	General	First general-purpose computer (ENIAC)
1950s	Monitoring	US NOAA WSR-57 weather radar network started
	Meteorology	First operational NWP models
	Meteorology	World Meteorological Organisation (WMO) established
	Warning	Research on social factors in response to natural hazards (Fritz)
1960s	Monitoring	First NASA TIROS satellite launched (polar orbiting/infrared)
	Monitoring	WMO World Weather Watch programme established
	Hydrology	Degree-day method for snowmelt (Martinec)
	Hydrology	Widespread R&D into conceptual rainfall-runoff models
	Hydrology	Blueprint for physically-based distributed models (Freeze and Harlan)
	General	Development of Kalman filtering techniques (Kalman)
1970s	Monitoring	First geostationary earth observation satellites launched (SMS-A, B)
	Monitoring	European Space Agency (ESA) Meteosat I satellite launched
	Monitoring	NOAA/NASA GOES satellite programme started
	Monitoring	ALERT radio-based protocol introduced (National Weather Service)
	Hydrology	Flash Flood Guidance technique introduced (National Weather Service)
	Hydrology	Widespread R&D on data-driven models for hydrological forecasting
	Warning	Introduction of email and internet protocols
1980s	Meteorology	First operational ocean–atmosphere coupled NWP model
	Hydrology	Ensemble Streamflow Prediction (ESP) method (Day)

(continued)

Table 1.6 (continued)

Period	General area	Description
1990s	Monitoring	TRMM space-borne precipitation radar launched
	Monitoring	Doppler weather radar network established (NOAA)
	Meteorology	Operational ensemble meteorological forecasting (ECMWF, NCEP)
	Hydrology	Hydrodynamic models publicly/commercially available
	Hydrology	Increasing sophistication of the land-atmosphere component in NWP
	Warning	GSM and SMS mobile telephony services introduced
2000-on	Monitoring	Increasing availability of multi-sensor precipitation products
	Monitoring	Development of X-band and phased array weather radar techniques
	Monitoring	Dual polarization radar upgrades started in the USA and elsewhere
	Meteorology	Operational implementation of mesoscale and convective-scale models
	Meteorology	Development of probabilistic nowcasting techniques
	Hydrology	Increasing use of probabilistic flood forecasting systems
	Hydrology	Increasing use of two-dimensional hydrodynamic models
	Hydrology	Real-time application of distributed physical-conceptual models
	Warning	Multi-media warning dissemination systems available commercially
	Warning	Widespread adoption of social media networks

Item	Time delay (initial)	Time delay (revised)	Actions taken
Monitoring	1 hour 15 minutes	37 minutes	• Reduced the telemetry polling interval from 1 hour to 15 minutes • Arranged an improved data communication link for receiving rainfall data and forecasts from the meteorological department
Forecasting	40 minutes	12 minutes	• Upgraded the computing equipment for the forecasting model • Reviewed and streamlined the approach to ensemble forecast generation • Simplified/rationalised the hydrodynamic component of the model
Warning	45 minutes	15 minutes	• Developed a new decision-support tool to help forecasters in deciding when to issue warnings • Adopted a new multi-media phone dialling/email/text message warning system including text-to-voice options and warning message generation tools and templates
Response	2 hours	1 hour	• Permanently pre-positioned key emergency response equipment on site, including demountable defences and road-closed signs • Appointed/trained local civil protection volunteers to help with issuing warnings and the emergency response
TOTAL	4 hours 40 minutes	2 hours 4 minutes	

Fig. 1.8 Illustration of some ways in which the average time delays in the flood warning process can be reduced, from the perspective of a flood warning service, for the idealized case of a very short-lived intense rainfall event. All values shown are illustrative only and a full analysis would consider the likely range and the uncertainty in the estimates

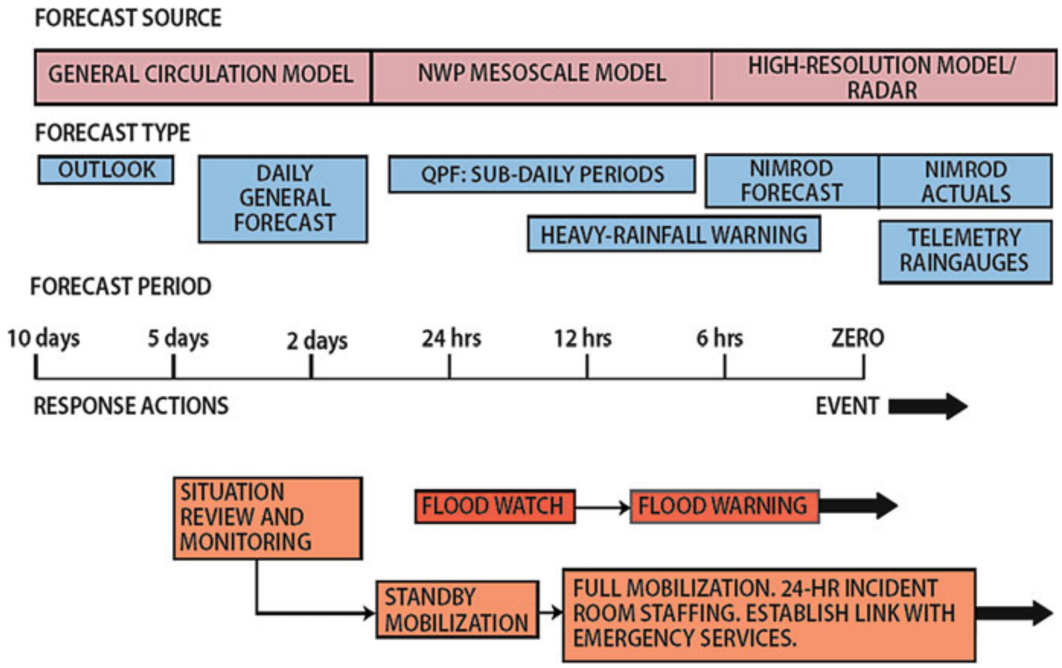

Fig. 1.9 Schematic of flood-forecasting lead time (World Meteorological Organisation 2011, courtesy of WMO)

More generally, as experience is gained with using a flood warning system and the technology is improved, views on what is possible often change. For example, in some countries a site-specific flood warning service is offered to locations where the typical response time between rainfall and the onset of flooding is as little as 1–3 h, whereas in others this would still appear to be a very challenging target. The use of rainfall and flood forecasts also provides the potential to extend a warning service to smaller, headwater tributaries, of the types prone to flash flooding. For example, in some locations, exploratory analyses might show that the only way to achieve sufficient warning lead time could be by using a flood forecasting model with observed or forecast rainfall inputs. Warnings could then possibly be issued primarily on the basis of a forecast, rather than observations alone although, as discussed in later chapters, this is a developing area requiring extensive performance testing before forecasts are used operationally. However, more generalized alerts at a catchment or district scale are widely used, based on rainfall depth-duration thresholds and – for rivers – flash flood guidance approaches (see Chaps. 8–11). Distributed rainfall-runoff modelling techniques are also increasingly used to provide flood watches and warnings for ungauged catchments (see Chaps. 5, 8, and 12). New developments in monitoring and forecasting techniques have also helped some organisations to introduce a warning service for other types of flash floods, such as debris flows and ice jams.

As discussed in later chapters, for a 'state-of-the-art' flood warning service, the monitoring techniques used typically include raingauges, weather radars, river gauges, and other sensors as required, such as for monitoring debris flows and reservoir operations. This increasingly includes the use of multi-sensor precipitation estimates, nowcasts and mesoscale model outputs as inputs to flood forecasting models. Typically these are available in the form of grid-based values transmitted automatically from meteorological services at intervals of minutes to hours, depending on the approaches used. Flood forecasting model outputs are usually updated based on real-time observations in a process known as data assimilation. The decision to issue warnings is then typically made on the basis of critical thresholds being exceeded, with real-time decision support systems and ensemble and probabilistic forecasts increasingly used as part of this process.

However, it is worth noting that at present not all organisations are able to operate systems of this type. For example, in a review of 86 countries (World Meteorological Organisation 2006b), about one third reported well-established national flood forecasting and warning services, with intermediate, basic, insufficient or no services elsewhere. Also, about 40% reported the need for strengthening or modernization of hydrometeorological observing networks in general or specifically for flood forecasting purposes (although the review noted that improvement programmes were already underway in a significant number of countries). Manually operated community-based flood warning schemes also offer a possible option where budgets or other issues do not allow a more automated approach.

Regarding probabilistic flood forecasting techniques, these potentially allow a more risk-based approach to the issuing of warnings and provide additional information to end users to help with decision making, combined with greater transparency in the overall process (e.g. Krzysztofowicz 2001; Schaake et al. 2007). This topic is discussed further in Chap. 12 and is an active area for research, with a number of operational and pre-operational systems implemented in recent years (e.g. Cloke and Pappenberger 2009). However, as with any new technique, the implications and benefits need to be assessed throughout the monitoring, forecasting, and warning process. The background to this approach and example applications are presented in several later chapters, whilst Chap. 12 discusses some recent research developments in this topic.

1.6 Summary

- The term ‘flash flood’ is typically considered to encompass several types of ‘short-fuse’ or rapid-onset event, including river floods, debris flows, glacial lake outburst floods, and floods resulting from ice jams, surface water in urban areas, dam breaks and levee breaches
- Many different definitions of flash floods have been proposed and typically these fall into the following three general categories: definitions based on typical catchment response times, definitions which consider the time available for an effective emergency response, and definitions based on absolute or relative values for catchment and/or storm scales

- Flood risk modelling and risk-based techniques are widely used in flash flood applications both to help to assess the risk to people and infrastructure and as a basis for prioritizing structural and non-structural interventions, including the development of warning systems. In addition to probability and consequence, the vulnerability of individual groups needs to be considered
- As for other types of flooding, the aim of a flash flood warning system is usually to provide people with more time to prepare for flooding to reduce the risk to life and property. With sufficient lead time actions can sometimes also be taken to reduce the extent of flooding both at individual properties (e.g. by using sandbags) and on a community-wide basis (e.g. by installing demountable defences or operating flood control structures)
- Regarding warning lead times, although typical minimum requirements for different types of response (e.g. evacuation) are presented in the literature, the actual values need to be considered on a case-by-case basis. These depend on a wide range of factors, including the catchment response time, the times needed for decision-making and issuing warnings, and the level of preparedness within communities and emergency response organisations
- The warning process is often conceptualised as consisting of the following key components: preparedness, monitoring, forecasting and warning. To increase the effectiveness of a warning system, improvements are typically required in all of these areas, considering both social and technical factors. A community-based (people-centred) approach is widely recommended, with particular attention to vulnerable groups. This is often termed a total or end-to-end warning system
- For flash floods, a key priority is often to reduce the time delays throughout the system to increase the warning lead time provided. Flood forecasting models are also increasingly used to assist staff with operational decision-making and issuing warnings earlier than is possible from observations alone. In some organisations the resulting improvements have changed views on what constitutes a 'flash flood'
- Internationally, there are several approaches to organising a flood warning service, with many differences in the technologies used and legislative environments. A typical progression is to move from an approach based primarily on monitoring river levels to one which also uses rainfall observations and forecasts and flood forecasting models, and covers a wider range of types of flash flood. Often this includes the introduction of performance monitoring, post-event reporting and service level agreements as part of a long-term strategy for improvements
- Community-based systems are widely used in flash flood prone areas to complement regional and national systems. Volunteers and staff on site also play a valuable role in monitoring flash floods, with their inputs formalized in some cases through procedures and the use of decision support systems
- Technological developments continue to improve both the accuracy and lead time possible when providing warnings of flash floods. For example, probabilistic and ensemble forecasting techniques are increasingly used and have the potential to allow a more risk-based approach to issuing warnings. Developments in the internet,

smartphones and other communications technologies are also helping to make it possible to issue more targeted warnings than was possible in the past, to larger numbers of people, and to reduce some of the time delays in the warning process

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Chapter 2
Precipitation Measurement

Abstract Observations of rainfall are often required as part of the flash flood warning process. The main measurement techniques which are used are raingauges, weather radar and satellite precipitation estimation. Each approach has its own advantages and limitations and the methods are complementary to some extent, providing information at different spatial and temporal scales. This has therefore led to the increasing use of multi-sensor precipitation estimates which combine the strengths of each approach and use information from other sources, such as lightning detection systems and atmospheric models. Here an introduction is provided to these techniques and to the more general topic of estimating the uncertainties in the observed values.

Keywords Raingauge • Weather radar • Satellite precipitation estimate • Multi-sensor precipitation estimate • Meteorological observations

2.1 Introduction

Prolonged or heavy rainfall is often the main cause of debris flows and flash floods in rivers and urban areas, and can be a key factor for dam breaks and other types of flash flood. Rainfall observations are used in several ways in the flood warning process, including for raising alerts using rainfall depth-duration thresholds and flash flood guidance methods and as direct inputs to flood forecasting models (see Chaps. 8–11).

The most widely used monitoring techniques are raingauges, weather radar and satellites. Weather radar networks are typically operated by National Meteorological Services (NMS) together with a core national network of raingauges and other meteorological instrumentation (e.g. Fig. 2.1). Additional raingauges are often operated by river basin management, hydropower, water supply, flood warning and other authorities and as part of community-based flood warning schemes. By contrast, geostationary, polar and low-earth orbit satellites are operated by a range

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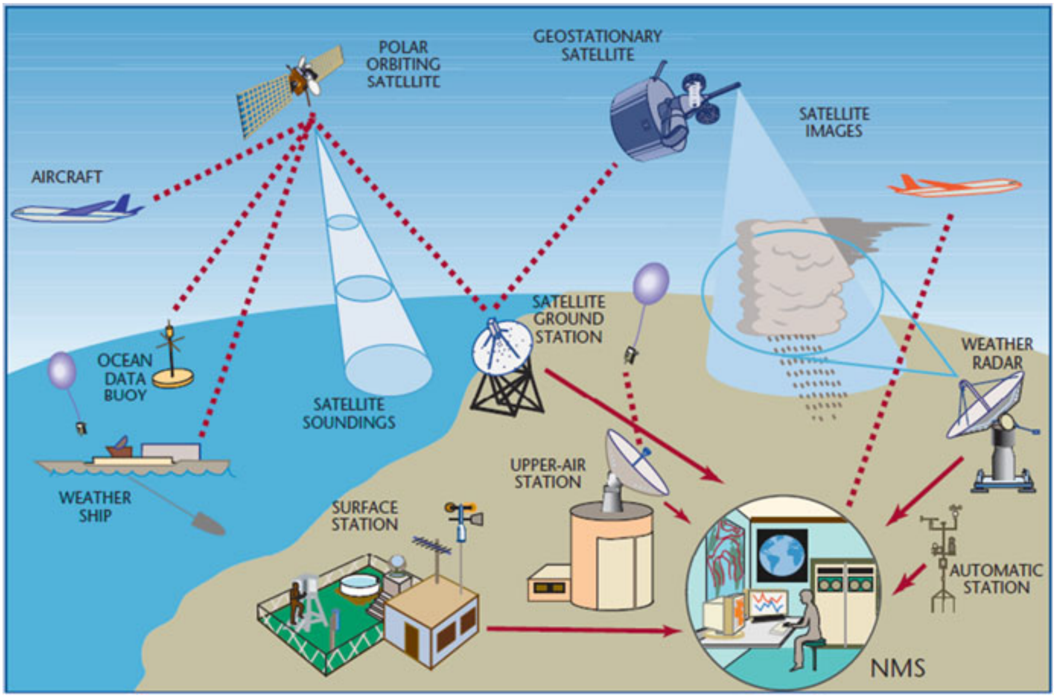

Fig. 2.1 Illustration of the Global Observing System, which is a fundamental component of World Meteorological Organisation (WMO) programmes and services. Data are collected from satellites, hundreds of ocean buoys, aircraft, ships and some 10,000 land-based stations. Within countries, the National Weather Service makes observations using manned and automatic instruments of temperature, precipitation, wind speed and direction, atmospheric pressure and other characteristics of the "weather". The observations, forecasts and products developed from these data are sent around the world every day, using the Global Telecommunication System (World Meteorological Organisation 2006, courtesy of WMO)

of international, national and private sector organisations for telecommunications, earth observation and other applications.

In countries where radar observations are available, these are usually used in preference to satellite-based estimates due to the higher spatial and temporal resolutions which are possible. However, satellite observations are often used to infill gaps in radar coverage and to assist with the post-processing of outputs. Raingauge observations are also widely used to check and adjust the outputs from weather radar and satellite-based systems, as well as being a primary source of observations. The choice of which approach to use in a particular flash flood application then depends on the spatial coverage at the location(s) of interest, past performance, organizational policy, budgets and other factors. Satellite precipitation estimates are also increasingly used in flash flood guidance applications in regions where the radar or raingauge coverage is poor or non-existent (see Chap. 8).

Of these three main approaches, one key difference is that raingauges record values at a point on the ground surface, whereas weather radar and satellite systems observe rainfall remotely either from a side-view or above. Raingauge observations are therefore often spatially averaged before use in flash flood warning applications whilst, for radar and satellite observations, some additional processing is required to infer values at the ground surface. The complementary nature of these techniques has therefore led to the increasing use of multi-sensor precipitation estimates (MPE) which aim to combine the best features of each approach. Here, the term 'precipitation' is used to describe all forms of liquid or solid water in the atmosphere, such as rain, snow, hail, sleet, drizzle and graupel. The latest methods also make use of other observation systems such as GPS humidity sensors, wind profilers and lightning detection systems, together with the outputs from Numerical Weather Prediction models.

This chapter provides an introduction to these techniques. The topic of measurement uncertainty is also discussed, with particular reference to weather radar observations. For example, in operational use, information on the spatial and time-varying structure of errors can help to decide how much credence to attach to observations, particularly when used as inputs to a flood forecasting model or a multi-sensor approach. As discussed in Chap. 12, there is also the potential to adopt a more risk-based approach to issuing flood warnings, based on a combination of the probability and consequences of flooding.

Later chapters discuss the related topics of telemetry systems (Chap. 3) and verification techniques for rainfall observations and forecasts (Chap. 4). More generally, the topic of precipitation measurement is an active area for research with many international and national initiatives underway, as illustrated by the examples in Chap. 12. It is also worth noting the role that the World Meteorological Organisation (WMO) plays in defining technical standards and producing guidelines, and some key publications in this area include World Meteorological Organisation (2000, 2007, 2008, 2011). Further information is provided in the many texts on this topic, including those by Strangeways (2007), Michaelides et al. (2008) and Testik and Gebremichael (2010).

2.2 Raingauges

2.2.1 Background

Raingauges are perhaps the most widely used approach for measuring rainfall. Gauges may be installed specifically for flood warning purposes, or for a range of water resources, agricultural and other applications. Most weather stations also include at least one raingauge and in some cases raingauges are installed at river gauging sites.

For manually operated (non-recording) raingauges, the rainfall depth is typically measured in a graduated cylinder at a fixed time each day by volunteers or paid observers; for example, the Community Collaborative Rain, Hail and Snow network (CoCoRaHS) network in the USA has more than 10,000 active observers (http://www.cocorahs.org/). A similar number report on weather conditions, snowfall and other parameters in the National Weather Service Cooperative Observer Program (http://www.nws.noaa.gov/om/coop/).

Fig. 2.2 Examples of raingauges at a weather station in the UK (*left*) and an IFLOWS installation in the USA (*right*). Integrated Flood Observing and Warning (IFLOWS) systems are widely used in flood warning systems in the eastern USA (e.g. see Box 6.1) and have similar origins to the ALERT protocol discussed in Chap. 3; here, the gauge is situated at the top of the structure, which also houses a data logger and telemetry equipment

In some applications, a larger storage gauge is operated alongside the manual gauge to provide a check on the cumulative daily totals over longer periods, such as at monthly intervals. These types of gauge are also useful in remote areas, where daily access is not possible. In some circumstances – for example, in post-event analyses following a major flash flood event – buckets, discarded containers and other receptacles may also provide a useful guide to the amount of rainfall which has fallen.

For automated gauges, a wider range of techniques is used. For example, for tipping bucket raingauges (e.g. Fig. 2.2), the principle of operation is that wedge-shaped 'buckets' on a lever arm alternately fill, causing the lever to tip, allowing the water to drain away and the second receptacle to take its place. The mechanism is calibrated to tip when a given volume of water has been collected, expressed as a depth of rainfall. Each tip then generates an electrical signal suitable for recording by an electronic data logger and, if required, conversion by a modem into a form suitable for telemetry transmission (see Chap. 3). Typically, when gauges are purchased, the recording depth is chosen according to the anticipated rainfall intensities at the gauge location. For example, 0.2 or 0.5 mm gauges are widely used in flood warning applications.

Another automated approach to measuring rainfall is to use instruments which rely on the weight or depth of water collected. For example, vibrating wire, strain gauge or load-cell approaches are typically used in weighing raingauges, and electrodes or floats to record depths. Drop-counting devices (or disdrometers) are also widely used in calibration studies for weather radars and in an increasing number of other applications. Typically these use optical or laser transmitters and receivers a short distance apart which detect the number, size and/or velocity of droplets and other types of precipitation passing through the beam (e.g. Fig. 12.1). Alternatively, in impact types, a piezoelectric sensor is used to count the number of droplets striking the surface, together with the impact forces to provide an indication of the size of each drop. A related approach is to design the gauge so that the size of passing into the instrument is almost independent of rainfall intensity, so that only the number needs to be counted.

Impact types, in particular, form a small, low-maintenance device with no moving parts and are increasingly used in road weather information systems and urban areas. Microwave-based systems with a range of kilometres also show promise as a way of estimating the path-averaged rainfall and are discussed in Chap. 12. Another solid-state option is a hot-plate gauge which consists of two heated plates, upward- and downward- facing, which are designed to measure both snow water equivalent and rainfall. The precipitation rate is estimated by 'calculating the power required to either melt or evaporate snow or to evaporate rain on the upward-facing plate, compensated for wind effects by subtracting out the power on the lower, downward-facing plate' (Rasmussen et al. 2011).

For flash flood applications, automated gauges are generally preferred if budgets allow, typically using 1-, 5- or 15-min recording intervals. However, it is worth noting that manually operated gauges are used successfully in many community-based flood warning systems, supported by a network of volunteer observers (e.g. Box 1.2). Low-cost automated raingauge and weather station instruments are also increasingly used by weather enthusiasts, with the web-based outputs providing another potentially useful source of information to national meteorological and hydrological services.

The choice of the type and make of gauge to use depends on a number of factors, including performance, cost, reliability, maintenance requirements, organisational standards and the level and quality of vendor support. However, a 2008/2009 World Meteorological Organisation survey of techniques for measuring solid precipitation at automatic weather stations (Nitu and Wong 2010) suggested that, at that time, the most common type of instrument in use in national meteorological and hydrological services was the tipping bucket raingauge (approximately 83% of responses). The next most widely used option was the weighing raingauge (16%) and, across all types, the most common reporting intervals were either 1-min or hourly. However, wide variations were reported in terms of manufacturers and gauge orifice areas, capacity, sensitivity and other factors. The survey also focused on national services and the preferred types may differ in local and regional organisations.

2.2.2 Interpretation of Observations

As with other types of instrumentation, there are some limitations on the accuracy of observations from a raingauge. In addition to the calibration and electromechanical issues associated with each type, a number of other factors can be important. For example, during high winds, errors often occur due to local distortions of the wind field around the gauge, and splashing sometimes occurs in heavy rainfall.

Wind effects from nearby buildings, hills and trees may also affect readings and low-lying gauges are also potentially at risk from being submerged by flood waters.

To assess and reduce wind-related problems, so-called 'reference gauges' are sometimes installed, in which the gauge is located in a mesh-covered pit with the opening at ground level. Also, in colder climates, snowfall can affect readings or even block or cover the instrument, although this can be overcome to some extent by adding an electrical heater to the gauge and/or a wind shield or snow fence. Maintenance issues sometimes also cause problems; for example, with vegetation growing around the gauge, or grass cuttings, sand, insects or falling leaves blocking the instrument.

To help to avoid these issues, many countries have national standards for the installation and operation of raingauges and for assessing the uncertainty in outputs. These are typically based on international guidelines and the findings from intercomparison experiments (e.g. World Meteorological Organisation 2008; Sevruk et al. 2009; Vuerich et al. 2009). Some examples of the types of siting criteria which are used include maximum heights above the ground and minimum distances to obstacles of a given type or height, such as trees or buildings. However, for flood warning applications, for reasons of cost, practicality, security and other factors, compromises are sometimes made compared to the ideal installation. There may also be technical reasons for installing raingauges at greater heights above ground level than standard and accepting the resulting reductions in accuracy; for example in locations where extensive snow cover is a regular occurrence or flooding is a potential risk.

When measurements are received via a telemetry system, these are typically screened for outliers through comparisons with historical maximum values and readings from nearby gauges. Suspect values are then flagged for further investigation. In multi-sensor systems (see Sect. 2.5), other types of observations are often used as part of this quality control process, such as those from weather radar, satellite, or lightning detection systems. For example, this may help to confirm that an unusually high value could have been due to a storm, or that a long period of zero values was due to the gauge being frozen or blocked by snow. For flood warning applications in particular, a key requirement is to identify and remove or correct anomalous values in near real-time without unintentionally removing genuine extreme observations. Empirical corrections are also widely used to help to compensate for wind-effects and other types of error (e.g. World Meteorological Organisation 2009).

In many cases, spatial estimates of rainfall are required from a network of raingauges; for example, to help with weather radar signal processing (see Sect. 2.3) and for some types of flood forecasting models (see Chap. 5). The methods used range from simple Thiessen polygon and inverse distance approaches to surface fitting techniques such as Kriging and spline and multiquadric approaches (e.g. Creutin and Obled 1982; Tabios and Salas 1985; Seo 1998; Goovaerts 2000; Daly 2006). For the more complex approaches, the analyses are often performed with the assistance of digital terrain models and Geographic Information System (GIS) tools. Some techniques also provide an estimate of the uncertainty arising from the spatial averaging process.

Although it is difficult to generalize, simpler techniques are usually used primarily in low-lying or flat terrain and/or where rainfall events are typically reasonably extensive and homogeneous, such as with widespread frontal storms. By contrast, the more complex techniques tend to perform better in complex terrain particularly if additional variables such as elevation or aspect are included in the analysis, such as with co-Kriging approaches. Geostatistical approaches are also widely used in weather radar raingauge adjustment schemes (see Sect. 2.3). However, for all methods, the density of the raingauge network is a key factor which determines the accuracy of the results, particularly for convective events.

By contrast, schemes which require expert judgement or interactive computer processing – such as isohyetal techniques – are rarely used in flash flood warning applications due to the lack of time for manual inputs. However they are widely used in post-event analyses of flash flood events due to the greater accuracy which is sometimes possible. Another practical challenge can arise when the records from several organisations need to be combined, perhaps using the outputs from different types of gauges using different reporting intervals and quality control standards. This typically requires extensive studies to decide how best to combine the data from the sources available.

More generally, when developing a catchment averaging scheme, observations from manually-read gauges are often included in the analysis since network densities are usually higher than for telemetered gauges. Although values are typically only available on a daily basis, they can provide an indication of storm total rainfall, and sometimes reveal spatial variations in rainfall which could be incorporated into a real-time averaging scheme, such as rain-shadow areas and influences from elevation or aspect. Other factors which are sometimes considered include indicators which describe the influence of features such as the slope, inversion-height characteristics, storm-directions, coastal influences, and types of event (frontal, orographic, convective etc.). Again, a GIS-based approach is widely used for these types of analyses; for example interpreting real-time observations by reference to a grid-based precipitation climatology (e.g. Daly et al. 1994; Zhang et al. 2011).

If archived weather radar observations are available, these can provide a useful comparison, and might in some cases lead to the decision to use radar-rainfall estimates as input to any flood forecasting component. For example, time sequences of radar images for major storms sometimes show consistent patterns for storm tracks, speeds and scales, and indicate areas of orographic enhancement. Comparisons with observations for individual raingauges or on a catchment-wide basis might then suggest giving a greater weighting to some gauges. Where budgets allow, experimental studies using dense networks of raingauges are also useful for investigating the spatial distribution of rainfall and developing catchment averaging techniques (e.g. Krajewski et al. 2003; Villarini et al. 2008; Volkmann et al. 2010).

However, for flash flood applications, one challenge is that the gauge densities required are often higher than for many other applications. The requirements vary between types of flash flood and some examples are provided in later chapters. Also, a more general issue is that, due to access difficulties and lower population densities, the spatial coverage of gauges is often poor at high elevations with – at best - only a few real-time gauges available, such as at major reservoirs and experimental sites. In these situations, another approach to assessing the adequacy of the gauge coverage is to investigate the likely impacts of the resulting uncertainties on forecasting model performance at the lead times of interest. For example one possibility is to compare the model performance - with and without data assimilation - using different choices of raingauges and averaging schemes, including any non-telemetered gauge records available. There have been many studies of this type although results tend to be specific to individual catchments, models and applications (see Chaps. 8–12).

2.3 Weather Radar

2.3.1 Background

Radar technology was first introduced operationally in the 1930s as a way of tracking aircraft. Experimental trials for meteorological applications began soon after the Second World War when it was realized that the interference from rainfall could be useful as a way of remotely observing precipitation. One of the first national systems was the WSR-57 network in the USA for which the first radars were installed in 1959. Many other countries soon followed although, due to cost and other factors, there are still a number with just a few sites serving major airports or population centres, or none at all.

Where a network is available, the resulting rainfall intensity images are widely used in flash flood applications; for example to track the progress of thunderstorms. The precipitation estimates are also used as a basis for short-range rainfall forecasting (or nowcasting; see Chap. 4) and as an input to real-time flood forecasting models and flash flood guidance approaches (see Chaps. 5 and 8). Meteorological services are also increasingly using weather radar outputs as part of the data assimilation process for mesoscale and convective-scale forecasting models (see Chap. 4).

The basic principle of operation is that an electromagnetic (microwave) signal is transmitted and the backscattered energy is recorded from rainfall and other objects. Magnetron or klystron transmitters are normally used. The signals are transmitted in pulses with the time delay – or 'listening' time – between transmissions much longer than the time of the pulse itself. If precipitation is encountered, the power of the reflected signal can be related to the range and a parameter called the radar reflectivity factor which depends on the drop size distribution. With certain key assumptions (see later), the reflectivity can then be related to the rainfall intensity at the ground surface whilst the time delay between transmission and reception provides an indication of the range.

The signal is transmitted from an antenna dish which is typically rotated at a few revolutions per minute and protected from the elements by a radome. The antenna is normally mounted on a steel or concrete tower, with key equipment kept in one or more nearby buildings (e.g. Fig. 2.3).

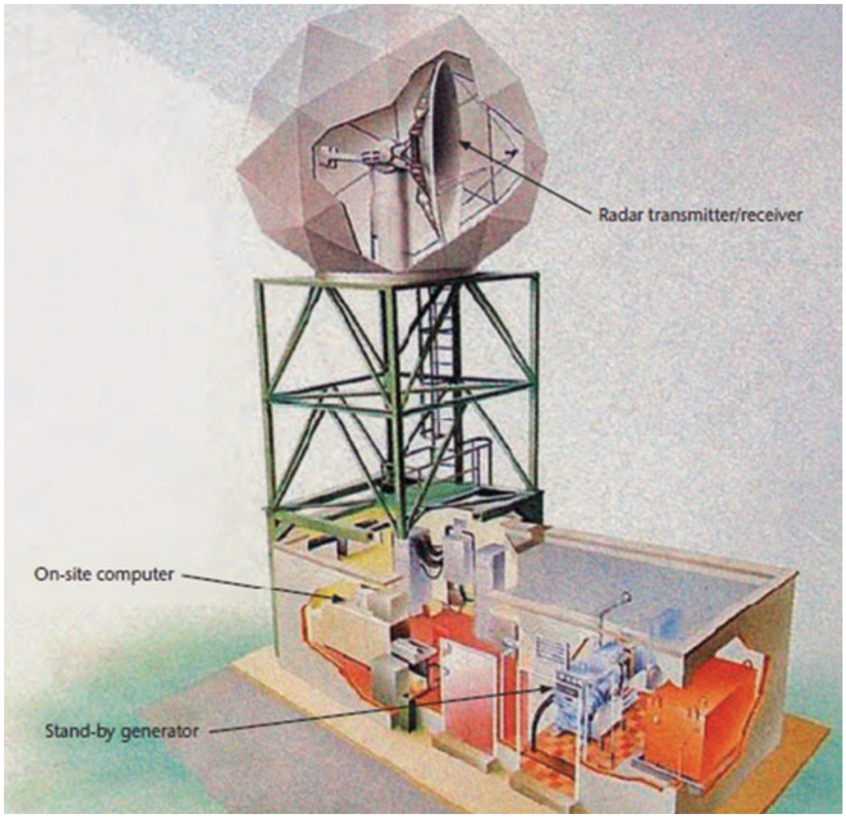

Fig. 2.3 View of the internal workings of a weather radar (Met Office 2009; Contains public sector information licensed under the Open Government Licence v1.0)

To provide an indication of rainfall and wind variations with altitude, several scanning angles are typically used with a full-volume scan completed over a period of several minutes. Beam angles typically range from horizontal or slightly above the horizontal to several degrees or more, and slightly negative angles are sometimes used in mountainous areas to view precipitation below the elevation of the instrument. In some systems, the scanning strategy can be adjusted depending on the current atmospheric conditions; for example, by using a faster rotation rate with more scan elevations for a rapid assessment of heavy rainfall, or a slower rate with fewer scan elevations to increase the sensitivity for wind profiling in clear-air.

The transmitting frequency used is normally in the C- or S-band, with wavelengths of about 5 and 10 cm respectively (e.g. Fig. 2.4). S-band instruments have a longer range and suffer less from signal attenuation in rainfall at a given range; however, they usually cost significantly more than C-band devices and are less sensitive to lighter rainfall. To provide an indication, the price of a modern C- or S-band instrument and associated infrastructure is typically of the order of one-million dollars or more, although costs continue to reduce as the technology improves.

At the network design stage, in addition to cost considerations, the choice of sites, wavelength, beam width, scan angles and other design features is typically made on the basis of detailed studies of a number of factors (e.g. Leone et al. 1989;

Fig. 2.4 Example of a Met Office C-band weather radar in the UK (*left*) and a NOAA/National Weather Service S-band (NEXRAD) radar in the USA (*right*) (Met Office 2009: Contains public sector information licensed under the Open Government Licence v1.0, and courtesy: National Oceanic and Atmospheric Administration http://www.erh.noaa.gov/)

World Meteorological Organisation 2008). These typically include site access considerations, local topography and typical storm and rainfall characteristics in a region (scale, locations, intensities etc.), and the intended applications (e.g. flood warning, aviation, weather forecasting). In some cases this includes field experiments using raingauge, satellite, drop-size (disdrometer) and other observations. Risk-based or multi-criteria analyses are also increasingly used to assess the suitability of a network for each proposed application; for example in terms of the coverage in urban areas or for catchments which have a high flood risk.

For individual radars, the practically useful detection range depends on a number of factors, including the local topography and the elevation of the instrument, but is typically about 200–300 km for C-band devices and more for the S-band. However, due to the curvature of the earth, at the maximum range the beam is typically at a considerable altitude even for the lowest scan angle. The spatial resolution also decreases due to the spread of the beam. For example, "a nominal 1° beam spreads to 0.9, 1.7 and 3.5 km at ranges of 50, 100, and 200 km, respectively", with a beam at an elevation of 0.5° approximately 4km above the Earth's surface at a range of 200km (World Meteorological Organisation 2008). For quantitative estimates of rainfall intensity – rather than images – the practically useful range is therefore less than the maximum detection range and can vary significantly between seasons due to atmospheric and other influences.

In operational use, the backscattered power is usually related to rainfall using a power law relationship between reflectivity and rainfall rate or intensity (Marshall and Palmer 1948). Typically the parameters in the relationship are calibrated based on comparisons of raingauge and radar estimates of rainfall, and in some cases from more detailed investigations using disdrometers and other meteorological instrumentation. The resulting relationships are then optimized for typical storm conditions in a region. When the drop size distribution varies from these conditions the outputs may under- or over-record rainfall; for example in exceptionally heavy rainfall or light drizzle. However, in some systems, it is possible to select alternative coefficients depending on the time of year or the operator's view on the most appropriate form to use in the prevailing conditions; for example by choosing stratiform, convective or tropical rainfall options.

Since the 1970s, instruments have increasingly been equipped with Doppler capability such that it is nowadays a standard feature in most networks. The resulting variations in phase or frequency between successive pulses then allow an estimate to be derived for the velocity of hydrometeors in the pulse volume (rain, snow, hail etc.). Since this depends on both the size and type of object, this can help to discriminate between rainfall and other types of precipitation, and false echoes such as those from aircraft, birds, insects and ground clutter.

A more recent development has been to retrofit existing radars with dual polarization capability and to make this standard for new instruments. This is sometimes referred to as a dual-pol. approach and falls within the more general category of polarimetric or multi-parameter approaches. Here, rather than just using a single plane (usually, but not always, horizontal), the microwave pulse is transmitted with both horizontal and vertical polarization and the characteristics of the reflected signal are recorded in both planes. As discussed in Box 2.1, this allows a number of additional parameters to be calculated which provide further information on the type and intensity of precipitation, and greatly assist with the quality control of observations. This approach has recently started to be used operationally in a number of national weather radar networks, including those in the USA, UK, France and Japan.

The operational use of X-band radars – which have a wavelength of about 3 cm and a range of about 30–60 km or more – is another recent development, although they have been used in research for many years. One limitation is the shorter range and greater signal attenuation from rainfall than for C- and S-band instruments. However, a major attraction is the lower cost and greater sensitivity to rainfall. It is also easier to find suitable locations for new installations; for example, a typical diameter for the antenna dish is of the order 1 m compared to about 10 m for an S-band radar. Some typical applications are to support heavy rainfall and flood warnings near major population centres and for rainfall detection in regions with complex terrain, thereby supplementing and 'filling gaps' in the national network coverage. Some locations where this approach is used or under development include parts of the USA, Japan (see Box 10.1) and Denmark (e.g. Pedersen et al. 2007; Maki et al. 2010; McLaughlin et al. 2009). Another development is the use of adaptive or 'agile' scan strategies to focus monitoring effort on the areas of most rapid storm development (see Chap. 12).

In some cases, mobile C- and X-band radars are also used in flash flood applications, and are typically transported on a truck to be installed where needed for a few weeks or months (see Box 9.1 for example). In the USA significant investments are also being made in a new generation of solid state phased array radars, as discussed in Chap. 12. More generally, information on the types of instruments used internationally is sparse but some trends can be deduced. For example, in the National Weather Service NEXRAD network, S-band Doppler dual polarisation devices are the standard approach (see Box 2.1). The situation in Europe is more mixed, with a database of information for 30 countries (http://www.knmi.nl/opera/) indicating 32 S-band, 162 C-band and 2 X-band instruments, of which 170 were Doppler equipped and 38 used dual polarization (database version 1.18; 1 June 2012).

By contrast, in the first feedback from a World Meteorological Organisation survey, with responses from 66 countries – including the USA and parts of Europe – 11 countries stated that they presently had no weather radar systems (Sireci et al. 2010). Of the 48 countries which provided detailed information, the top three applications were for nowcasting, large scale weather monitoring and flood warning. Also, there was a roughly equal split between magnetron and klystron transmitters, but overall only 7% of instruments were said to have dual polarization capability. However, since the time of that survey, dual polarization upgrades have been completed in several of the countries surveyed.

Box 2.1 Dual Polarization Weather Surveillance Radar, USA

The National Weather Service has operated a network of weather surveillance radars since the 1940s and Table 2.1 summarises some key historical developments (NOAA 2010). The most recent change is the upgrade to dual polarization (dual-pol or polarimetric) capability. The basis of the technique is that microwave pulses are transmitted in both the horizontal and vertical planes, rather than just the horizontal. Modifications to the existing fleet of 159 radars were made to the antenna hardware and by providing additional signal and post-processing software, without affecting the existing scanning strategies, data resolution or reflectivity and velocity algorithms.

The availability of reflected power and phase information in two planes allows several new parameters to be calculated in addition to the reflectivity factor for horizontal polarization Z_h. These include (Ryzhkov et al. 2005; Scharfenberg et al. 2005; Schlatter 2010):

- The differential reflectivity (Z_{DR}) which is a measure of the log of the ratio of the reflected horizontal to vertical power returns. Z_{DR} is approximately zero dB for spherical hydrometeors and becomes positive when these are horizontally oriented and – much less frequently – negative when vertically oriented (e.g. in an electrical field). It provides an indication of the presence of hail and of the median rain drop shape and hence size
- The specific differential phase (K_{DP}) which is the mean rate of change of the differential phase per kilometre, where the differential phase is a measure

(continued)

Box 2.1 (continued)

Table 2.1 Some key developments in the weather surveillance radar network in the USA

Date	Description
1947	US Basic Radar Network started, based on converted radars from World War 2
1959	S-Band Weather Radar Surveillance network started (WSR-57 radars)
1971	First Doppler radar installed at the National Severe Storms Laboratory (NSSL)
1976	Installation of local C-band radars (WSR-74C) and additional S-band radars (WSR-74S)
1976–1979	Field tests of 4 Doppler radars as part of the Joint Doppler Operational Project
1984	First research trials of dual polarization radar at NSSL
1990–1997	Installation of the NEXRAD network of 159 S-Band Doppler radars (WSR-88D)
2002–2003	Joint POLarization Experiment at NSSL on dual polarization techniques (JPOLE)
2011–2012	Upgrade of the NEXRAD network to dual polarization

of the shifts (or lag) between horizontal and vertical phases; for example, due to passing through rainfall. The differential phase is near zero for spherical objects and higher for horizontally-oriented objects, with the magnitude of the change also increasing with particle concentration. It is useful for distinguishing between precipitation and other echoes, for identifying regions of high liquid content even in the presence of hail, and for estimating rain-rate

- The correlation coefficient (CC or ρ_{HV}) between horizontally and vertically polarized power returns. This is typically higher (close to 1.0; perfect correlation) for meteorological echoes that are fairly uniform in shape and size, such as rain and snow, and lower for more irregular shapes, such as clear air returns (blooms) caused by concentrations of birds and insects, and ground clutter. It is extremely useful for differentiation of precipitation vs. non-precipitation targets and for identifying melting layers, giant hail and airborne tornadic debris

In particular, some advantages of using the differential phase parameter include its immunity to radar calibration errors, attenuation in precipitation, and partial blockage of the radar beam (Ryzhkov et al. 2005). Various other correlation parameters can also be estimated between transmitted and reflected components although their relationship to precipitation characteristics is less well understood.

Based on extensive field trials (Ryzhkov et al. 2005; Scharfenberg et al. 2005), some key benefits which have been found include significant improvements to

(continued)

Box 2.1 (continued)

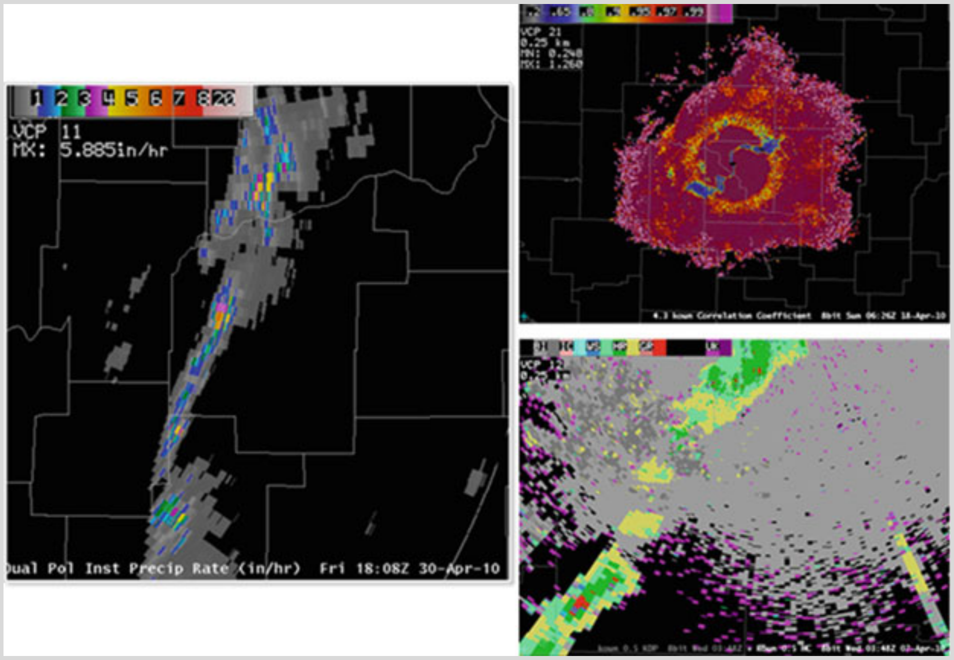

Fig. 2.5 Some examples of outputs from a dual polarization radar in Oklahoma. From the top right clockwise: Melting Layer Detection Algorithm outputs clearly showing a bright-band 'ring'; Hydrometeor Classification Algorithm outputs (HR = heavy rain, GR = graupel, WS = wet snow, IC = Ice Crystals, UK = Unknown); Dual-Pol QPE outputs showing the instantaneous precipitation rate in inches/hour (NOAA/National Weather Service; Schlatter 2010)

radar data quality and rainfall estimates, and an improved ability to distinguish rainfall echoes from other types of return, such as those caused by anomalous propagation and non-hydrometeors. For example Zrnic and Ryzhkov (1999) note that polarimetry has the potential to:

- Improve quantitative precipitation estimation
- Discriminate hail from rain and possibly gauge hail size
- Identify precipitation type in winter storms (dry/wet snow, sleet, rain)
- Identify electrically active storms
- Identify biological scatterers (birds, insects) and their effects on wind measurements; and
- Identify the presence of chaff and its effects on precipitation measurements

Other benefits include the ability to identify airborne tornadic debris and to provide qualitative improvements in precipitation estimates.

For the NEXRAD dual-polarization upgrades, in addition to the three base products described above, three new algorithms were made available (e.g. Fig. 2.5):

(continued)

Box 2.1 (continued)

- Melting Layer Detection Algorithm – which detects the melting layer based on reduced values for the correlation coefficient CC
- Hydrometeor Classification Algorithm – which makes a best guess of the dominant hydrometeor type for every beam elevation angle, using the following classification scheme: light/moderate rain, heavy rain, hail, 'big drops', graupel, ice crystals, dry snow, wet snow, unknown
- Dual-Pol QPE – an advanced precipitation estimation algorithm making use of dual-polarization parameters

2.3.2 Interpretation of Observations

As with any other type of instrumentation, there are a number of strengths and limitations with weather radar observations.

For flash flood applications, the most obvious advantage is the ability to observe precipitation over an extensive area, including catchments which have no raingauges. However, there is the intrinsic physical limitation that – for each scan angle – values are recorded above rather than at the ground surface, with the beam width and minimum detection height increasing with distance from the radar. Even the lowest beam may therefore overshoot some forms of precipitation, such as low-level orographic rainfall. Some other potential issues include blockage and ground clutter from mountains, buildings, wind farms and other obstacles, plus sea clutter for some sites. Also, for fast-developing storms, significant changes to precipitation and wind fields can occur in the time that it takes to perform a full volume scan.

To help to overcome some of these issues, when a network of radars is operated, the processed outputs are normally combined into a mosaic or composite image to make best use of all of the observations available. This is sometimes the only product available but in some cases single site raw and/or processed values are provided; for example to users who wish to use their own post-processing algorithms. Composite outputs are usually processed from the original polar scans to a grid-based format. For example, rainfall intensity values might be provided as 5-min accumulations on a 1 km grid around radar sites but with the resolution decreasing to 2 km and then 5 km at greater distances (although the values used differ between organisations). For multi-sensor precipitation products (see Sect. 2.5), the inclusion of other types of outputs is also being explored, such as military radars, the Doppler radars which are often used at major airports, and the privately-operated C- and X-band radars used by television stations in some countries.

To assist with interpreting outputs, maps of coverage are often produced and in some cases are made publicly available. For example, Fig. 2.6 shows one of the reflectivity products available from the national weather radar network in the USA.

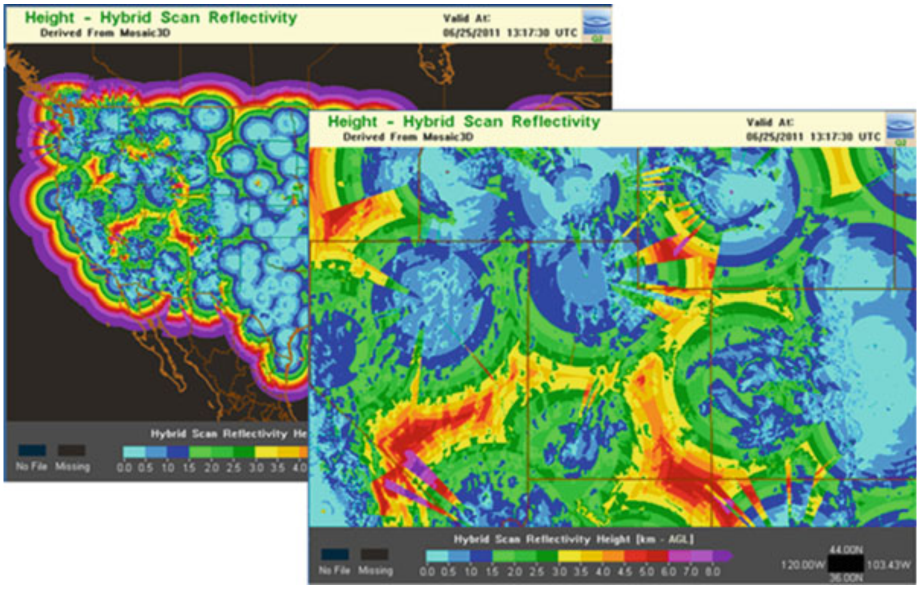

Fig. 2.6 Example of outputs for the hybrid scan reflectivity height (HSRH) from the US weather radar network on 25 June 2011. The *zoomed-in area* shows details for parts of Utah, Nevada and Colorado illustrating the gaps in coverage in these mountainous states. HSRH is the height of the lowest non-missing single radar hybrid scan reflectivity at each NMQ grid cell and has units of kilometres above ground level, where the NMQ product is discussed in Box 2.3 (http://nmq.ou.edu/)

Simpler pre-defined clutter maps or masks are also widely used to provide an indication of the maximum useful range. These are typically based on a one-off digital terrain model analysis taking into account topography, obstacles (buildings, wind farms etc.) and – in some cases – beam power distributions for standard atmospheric conditions. Long-term average values of the reflectivity may also reveal fixed artefacts in the observations and variations in performance in different seasons.

There are a number of other potential issues with the coverage and accuracy of observations and some key points are summarized in Table 2.2 and illustrated in Figs. 2.5 and 2.7. In some cases these issues also present opportunities; for example, for the study of insects and bats (in the emerging field of aeroecology) or to derive near-surface humidity estimates for data assimilation in atmospheric models, based on variations in propagation times to the locations of known ground clutter, such as nearby hills (e.g. Weckworth et al. 2005).

However, where possible corrections are usually applied to filter out or take account of these influences. The various stages in the analysis typically include signal-processing and quality control, hydrometeor classification and product generation (e.g. Collier 1996; Bringi and Chandrasekar 2001; Meischner 2004; World Meteorological Organisation 2008; Villarini and Krajewski 2010).

For example, one approach which has been widely introduced since the 1990s is to improve estimates for the surface precipitation using assumed values for the Vertical Profile of Reflectivity (VPR). Typically use is made of mean (climatological)

Table 2.2 Some factors which can affect the accuracy of weather radar observations of precipitation, in addition to uncertainties in rainfall-reflectivity relationships and physical limitations (ground clutter, range-related issues etc.)

Type	Item	Description
Hardware-related	Mechanical or electrical	Antenna pointing errors, electronic stability issues, downtime for maintenance or repair, signal interference from external sources
	Radome attenuation	Attenuation of the reflected signal due to wetting of the radome. A hydrophobic coating is often used to reduce this effect and correction algorithms are increasingly applied (e.g. storm emission-based approaches)
Atmospheric	Aeroecology	Reflections from concentrations of birds, bats and/or insects, sometimes called blooms or bloom echoes
	Anomalous propagation/ducting	Curvature of a beam due to variations in refraction arising from air temperature and humidity gradients, in some cases causing the beam to strike the ground. Sometimes referred to as anaprop
	Clear-air echoes	Minor influences on backscattered radiation due to variations in refractivity due to turbulence, inversions, wind shear etc.
Precipitation	Evaporation	Evaporation of precipitation beneath the lowest beam elevation
	Orographic enhancement	Low-level rainfall arising from topographic influences beneath the lowest scan height
	Snow and hail	Increased reflectivity from hail in convective storms and the 'bright-band' effect where snowflakes turn to rain; for example in some winter, stratiform conditions (e.g. Fig. 2.5)
	Updrafts/downdrafts	Influences on fall velocities from updrafts and downdrafts, particularly in convective storms
	Wind shear	Horizontal advection of precipitation, particularly beneath the lowest beam, with the effect most apparent for drizzle and light rainfall

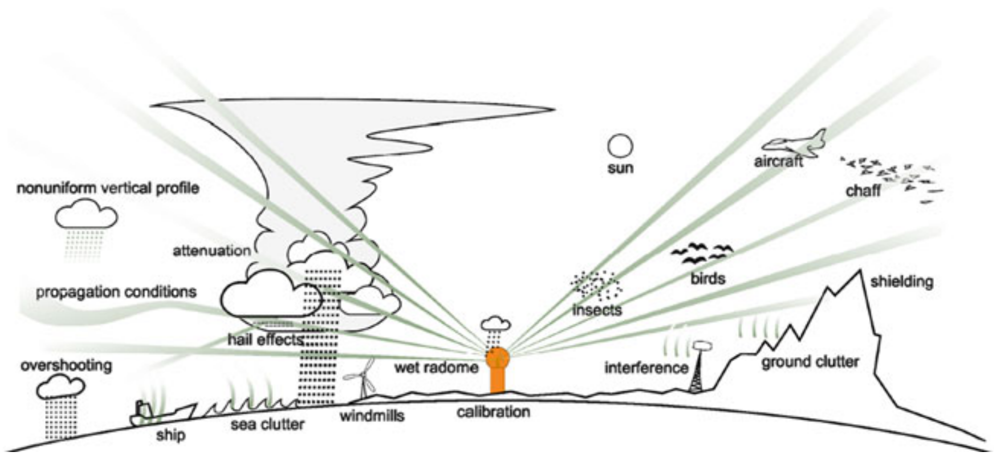

Fig. 2.7 Phenomena affecting radar data quality (Holleman et al. 2006 and OPERA, a project and operational service of EUMETNET EIG)

or parameterized values for the radar site or real-time estimates based on profiles measured near to the radar or averaged across parts of the scan volume. Profiles are typically applied on an area-wide or pixel-by-pixel basis, sometimes distinguishing between different types of precipitation (e.g. Fig. 2.9 in Box 2.3). In some cases, satellite observations and the outputs from atmospheric models are used as part of the correction process, such as for estimates of the freezing level and wind fields. In some systems, conceptual or statistical models are used to help to account for orographic and other local effects beneath the lowest beam elevation.

More generally, telemetered raingauge observations are widely used in adjusting radar outputs. Views differ on the best approach to use and, in some organisations, whether real-time adjustments should be made at all. For example, where the raingauge coverage is sparse, adjustments can degrade rather than improve rainfall estimates in ways that are not easily anticipated. The technique also tends to work better for widespread frontal events where rainfall is relatively uniform, rather than for convective events. The main choices are to apply adjustments in real-time, or to use typical bias and other correction factors derived over the past few days or more (e.g. Wood et al. 2000; Gjertsen et al. 2004). In some cases, hybrid versions are used which combine aspects of both approaches.

The adjustments are typically expressed in the form of functions of the ratio between radar and raingauge values at and around coincident grid-squares. This could be as simple as a single mean-field value applied across the whole domain, or range-dependent or spatially-varying estimates. In the latter case, spatial interpolation techniques which are used include inverse distance, Kalman filter, Kriging, multiquadric and Bayesian approaches (e.g. Wilson and Brandes 1979; Todini 2001; Moore 1999; Seo and Breidenbach 2002). Some options for deciding on the best approach to use include analyses of past performance and field trials using dense networks of raingauges at experimental sites.

The use of raingauge data is sometimes described as bias-correction of radar observations. However there are also errors in raingauge observations and, in some adjustment schemes, an allowance is made for these uncertainties. More generally, raingauge-adjusted outputs can be regarded as a form of multi-sensor precipitation product, using just two observation systems. A next step beyond that is to use additional types of observations such as those from satellites and lightning detection systems, and this topic is discussed in Sect. 2.5.

2.3.3 Weather Radar Products

The outputs from a weather radar network are typically made available as a suite of products to meet the needs of a range of end users; for example, providing estimates for rainfall rates, wind speeds and directions, and other parameters. Boxes 2.1 and 2.3 show several examples of the types of output available. In some organisations, products are made available for several different stages in the processing of outputs, such as the following examples for rainfall rate:

- Single site – the raw reflectivity outputs; users then need to apply their own quality control and signal processing algorithms, including raingauge adjustments if applicable and the conversion from polar to grid coordinates
- Mosaic Level I – a basic quality controlled rainfall composite product, with no real-time raingauge adjustments, although possibly including weekly (or other) bias adjustments
- Mosaic Level II – as for Level I but including real-time raingauge adjustments and more sophisticated correction procedures
- Mosaic Level III – as for Level II but inspected by an experienced forecaster and – if appropriate – adjusted before distribution to end users
- Multi-sensor – automated products which use raingauge, satellite, lightning and other observations, and atmospheric model outputs, to improve estimates (see Sect. 2.5)

Here the different levels of output provided are just for illustration and the terminology used varies widely between organisations. For example, the following WMO classification is often adopted: Level I (primary data or instrument readings), Level II (meteorological variables and processed data) and Level III (derived meteorological parameters) (World Meteorological Organisation 2007). Typically several products are made available for parameters such as rainfall, wind profiles, and cloud top heights, together with newer types of products from dual polarization radars, where available. Increasingly outputs include data quality indices or other estimates for the uncertainty in outputs (see Box 2.2).

From a hydrological perspective, perhaps the best approach to deciding whether to use raingauge or radar-based estimates of rainfall is to compare the outputs over a number of rainfall events, ideally over a period of several years, both in terms of rainfall and when used as an input to flood forecasting models. For example, some meteorological services now maintain archives of radar observations dating back a decade or more. In some countries, long-term reanalyses of outputs are also planned or underway taking account of the impacts of changes in raingauge networks and radar hardware and signal-processing techniques during the analysis period

Box 2.2 Uncertainty Estimates for Weather Radar Products

For real-time operation, it is often useful to provide an indication of the uncertainty in weather radar products. For example, this information can be used when combining the outputs from multiple instruments to form a mosaic or composite, particularly in locations where this involves observations from more than one organization or country. Probabilistic outputs are also potentially useful for input to flood forecasting models (see Chap. 12) and in guiding the generation of ensembles in nowcasting approaches (see Chap. 4). Other potential applications include "validation of radar and rain gage data merging procedures, testing of various methods for computation of mean areal precipitation, and sensitivity analysis of rainfall-runoff models" (Krajewski and Georgakakos 1985).

Perhaps the most widely-used approach to date has been to provide data quality flags or indices as an indication of performance (e.g. Holleman et al. 2006; Einfalt et al. 2010). Values are typically presented on a scale of 0 to 1, 100 or 255 with associated metadata describing any vertical profile of reflectivity or other corrections applied. This information provides a guide on the confidence to attach to outputs and can be used in algorithms which combine the outputs from multiple sites into composite or mosaic products. It is also potentially useful when deciding whether to assimilate weather radar data into Numerical Weather Prediction models.

Both static (global) and dynamic (real-time) indices are used. Typically values are derived on a pixel-by-pixel basis, with static estimates based on physical limitations such as range, ground clutter, and beam height, or long-term (climatological) observations. By contrast, real-time values are typically based on pre-defined thresholds or confidence limits linked to reflectivity observations and possibly other information, such as satellite observations.

For example, following a Europe-wide survey, Norman et al. (2010) proposed three levels of complexity relying on: reflectivity and some global quality factors (level 1); incorporating 'climatological' data such as frequency of detection or clutter maps (level 2); and using additional dynamic information such as the height of the freezing level from Numerical Weather Prediction models (level 3). It was noted that users may wish to receive three types of quality information: the likelihood of an echo being from a hydrometeor, the quality of the reflectivity measurements, and the quality of the conversion of these values to a rainfall intensity at the ground surface.

Data quality indices also provide an indication of the uncertainty in outputs but there are some limitations with this approach. An alternative is to derive direct estimates for the error covariance matrix or simplified representations of it, such as an ensemble estimate. This approach aims to represent

(continued)

Box 2.2 (continued)

both the spatial and temporal relationships in the uncertainties in the precipitation field, although there are still numerous factors to understand about the error structure (e.g. Krajewski and Smith 2002). However, for flash flood warning applications, one potential advantage of deriving quantitative estimates of uncertainty is that – when used as input to a flood forecasting system – this can potentially assist in taking risk-based decisions based on a combination of probability and consequence, such as whether to operate a flood control gate or evacuate a residential area. However, this is a developing research area and is discussed further in Chap. 12.

There have been numerous off-line (simulation) studies of the uncertainties in weather radar observations, using stochastic, error decomposition and other approaches. Simulations of this type and practical experience generally suggest that the spatial sampling error 'decreases with increasing area size, increasing time period, increasing *(rain)* gage density, and increasing rainfall amount' (Wilson and Brandes 1979, reported by Krajewski et al. 2010). However, for real-time use, rather than trying to combine individual sources of error, with assumptions about their spatial and temporal inter-relationships, another approach is to derive an estimate for the overall error by comparisons with raingauge observations (e.g. Ciach et al. 2007; Germann et al. 2009; Mandapaka and Germann 2010). This can also be extended to include a consideration of the uncertainties in the raingauge observations themselves, and in satellite and other observation systems if using a multi-sensor approach (see Sect. 2.5).

(e.g. Delrieu et al. 2009; Moulin et al. 2009; Krajewski et al. 2010). The simulated values aim to reflect the current operational performance of the network and are potentially of great use in developing flood forecasting models and for other hydrological applications.

For real-time use, when radar outputs are used as inputs to a flood forecasting model, a number of other factors usually need to be considered. Typically these include the need to establish a reliable means of delivery (e.g. leased line, high-speed broadband), a service level agreement (or similar), data archiving facilities, and round-the-clock support arrangements. In some cases, additional software is required for receiving, viewing and post-processing the radar outputs and several systems are commercially available. If possible, a system of version control should also be established to notify end users of any significant changes in hardware or signal processing algorithms which might affect flood forecasting applications.

Many research studies have also been performed to compare the various weather radar products and analysis techniques which are available, and to share both observations and best practice. For example, in Europe, approximately 30 countries participate in the OPERA programme of EUMETNET (http://www.knmi.nl/opera/).

Similarly, for a World Meteorological Organisation intercomparison experiment, a prioritized list of Quantitative Precipitation Estimation (QPE) issues cited in the project concept document (http://www.wmo.int/) included:

- Ground Clutter and Anomalous Propagation
- Vertical Profile of Reflectivity
- Partial Occultation
- Reflectivity Bias Calibration (Monitoring)
- Attenuation Correction/Handling
- Minimize Impact of DSD (*Drop Size Distribution*) Variability
- Gauge Adjustment (function of density)
- Consistent verification and Data Quality Metrics
- Uncertainty/Scale/Probability Concepts

2.4 Satellite Precipitation Estimates

2.4.1 Background

Satellite observation systems have transformed many aspects of natural hazard monitoring since they were first introduced in the 1960s. For meteorological applications, some quantities which can be measured or inferred include (World Meteorological Organisation 2008):

(a) The temperature profile, and the temperature at the cloud top and at the surface of the sea and land
(b) The humidity profile
(c) The wind at cloud level and at the ocean surface
(d) Liquid and total water and precipitation rate
(e) Net radiation and albedo
(f) Cloud type and height of cloud top
(g) Total ozone
(h) The coverage and the edge of ice and snow

For flash flood applications, the images provided are typically used to help forecasters track the progression of frontal systems, tropical cyclones and other major features. However, as discussed in Chaps. 8–11, due to spatial resolution issues the quantitative use of satellite precipitation estimates has been limited to date except in regions with sparse raingauge coverage and no weather radar networks. More generally, though, satellite observations play an important role in data assimilation for Numerical Weather Prediction models (see Chap. 4) and in producing multi-sensor precipitation products (see Sect. 2.5). As discussed in Chaps. 3 and 12, observations of soil moisture, snow cover and land use are also potentially useful as inputs to distributed rainfall-runoff models.

The two main types of satellite system use geostationary and low earth or polar orbits. For meteorological observations, international coordination is provided by the Coordination Group for Meteorological Satellites (CGMS) which provides both design and operational support; for example by facilitating the temporary relocation of geostationary satellites in case of problems with any individual spacecraft (http://www.cgms-info.org/).

Geostationary satellites are placed into an orbit chosen to maintain a fixed position relative to a point on the ground, with an orbital height of about 36,000 km. For meteorological applications, approximately six satellites are required to provide complete coverage up to latitudes of about 55°, although polar-orbiting satellites need to be used as well for a full global coverage (World Meteorological Organisation 2007). Images are typically provided every 15–30 min in the visible, water vapour and infrared bands at a spatial resolution of 1–4 km. In some systems there is also the option to use a faster rapid-scanning mode to focus on smaller areas on the earth surface. Some satellites also include additional sensors for monitoring carbon dioxide, ozone and other constituents and for space observations.

Currently the main meteorological geostationary satellites are those within the NOAA GOES, European Meteosat and Japanese MTSAT (formerly GMS) programmes, together with those operated by India, China and the Russian Federation. For example, the GOES and Meteosat programmes include 2–3 primary satellites each. These are all operated by national or international agencies with data made available to national meteorological and hydrological services for use in weather forecasting and other applications. Since the 1970s, a number of replacement satellites have been launched within these programmes, with each upgrade providing additional functionality, resolution and reliability. The instrumentation used typically includes imagers and sounders. Data collection and distribution systems are often also included and are widely used for the telemetry of hydrological and meteorological data (see Chap. 3).

Polar and Low Earth Orbit (LEO) satellites by contrast are operated at much lower altitudes and therefore normally provide higher resolution observations, but move relative to a fixed location on the ground. For example, polar orbits typically have an altitude of 800–1000 km with an orbital time of about 100 min. Global coverage is then provided over a number of orbits. For a single satellite, the orbits used often mean that the time for which a location is visible in each day is quite limited, with intervals of much as 1–3 days for some low earth orbits. For example, one estimate suggested that, for US satellites alone, the 3-hourly coverage averages about 80% of the earth's surface for latitudes of up to 50° (Huffman et al. 2007) although this continues to improve. However, most meteorological satellites are placed into sun synchronous polar orbits so that the satellite passes twice over a given location on the equator at approximately the same time each day.

Microwave instruments are often carried on polar orbiting satellites for humidity, soil moisture and other observations. Several military, civil and commercially operated systems provide information which is potentially useful for natural hazard-related applications, or intended specifically for weather forecasting, such as those within the NOAA-N, NASA Aqua, European MetOp and NASA NPP programmes. The sensors carried vary between systems but some examples include the Special Sensor Microwave Imager Sounder (SSMIS; successor to SSM/I), Advanced Microwave Sounding Unit (AMSU), Microwave Humidity Sounder (MHS) and – for visible and infrared observations – the Advanced Very High Resolution Radiometer (AVHRR).

The outputs from research satellites are potentially also useful although do not necessarily have the same standards of availability and quality control as for operational satellites. For flash flood applications, one programme of particular interest is the joint US/Japanese Tropical Rainfall Measuring Mission, or TRMM (http://trmm.gsfc.nasa.gov/; http://www.eorc.jaxa.jp/TRMM/). This was the first satellite to carry a space-borne precipitation radar and this operates on the same principle as ground-based instruments although using the shorter K_u-band (wavelength ~2 cm) to provide a lightweight instrument and low power consumption.

The satellite was launched in 1997 for an anticipated 3–5 years although the mission was subsequently extended beyond 2010 due to the value of the information provided. It operates in an equatorial orbit at an altitude of approximately 400 km and with a path between about 35°N to 35°S, with 16 orbits per day and an orbital time of about 90 min. The horizontal resolution of the radar observations is approximately 5 km and the outputs have been used in numerous research studies and some operational applications. The satellite also carries visible and infrared scanning, microwave imager (TMI), lightning imaging and radiated energy instruments. It will be replaced by the more advanced Global Precipitation Measurement (GPM) mission constellation of satellites (Hou et al. 2008) which is potentially of great interest for flash flood applications (http://pmm.nasa.gov/GPM/) and is described in Chap. 12.

2.4.2 Interpretation of Observations

To interpret satellite observations, numerous corrections need to be applied for instrumental, atmospheric and other factors. Table 2.3 shows some examples of the types of derived outputs which are used in meteorological applications, in addition to the raw radiance and imagery outputs. Due to limitations on the coverage, accuracy and resolution of individual sensors, products are often based on the outputs from several sensors.

Precipitation products form another category and again are often derived from a combination of the outputs from different sensors and systems (e.g. World Meteorological Organisation 2000; Scofield and Kuligowski 2003; Vasiloff et al. 2007; Gebremichael and Hossain 2009; Sorooshian et al. 2011). In general terms, in addition to the TRMM radar-based approach (see previous section), the main types of technique include:

- Infrared/visible-based estimates – algorithms which typically make use of geostationary observations of cloud-top brightness temperatures and cloud extent

Table 2.3 Some examples of the types of satellite-based products which are used in meteorological applications (categories based on World Meteorological Organisation 2007)

Category	Typical inputs	Examples of products
Cloud characteristics	Visible, infrared	Cloud top temperatures, types, heights, masks etc.
Atmospheric temperature and humidity soundings	Infrared, microwave	Vertical profiles of air temperature and humidity
Atmospheric motion winds	Sequences of cloud, water vapour or ozone images or fields	Estimates for wind speeds and directions at various levels
Land and sea surface temperatures	Infrared (cloud-free), radiometers, microwave (sea temperatures)	Estimates with various spatial resolutions and coverages
Snow and ice	Visible, infrared, microwave	Spatial coverage, plus snow depth estimates for active microwave instruments
Vegetation	Visible, infrared	Vegetation type and growth, leaf area index etc.
Ocean surface	Microwave (active), scatterometer	Sea-level (altimetry), significant wave height, wind intensity etc.

and morphology to estimate rainfall intensity. A key assumption is that rainfall intensities at the ground are greater for deeper formations, which reach higher altitudes and hence lower temperatures. This assumption applies primarily to convective clouds and is less valid for other types, such as cirrus, stratiform and orographic cloud, and for situations with appreciable wind-shear of cloud tops. In addition to images at a given time, life-history approaches are sometimes used to provide information on the stage of development of a cloud system based on a sequence of images. Products of this type started to become available operationally soon after the first geostationary satellites were launched in the 1970s

- Microwave-based estimates – algorithms which use passive microwave observations from polar orbiting satellites to infer the water and ice content of cloud formations based on emissions of cloud water. This technique generally works best over the oceans where there is a sharp contrast with the background levels of radiation. Over land, a different approach is used, which is to observe the masking effect of cloud on brightness temperatures. This works best in situations where there are significant amounts of cloud ice particles present, and less well for warmer orographic cloud, for example. The first operational products of this type were based on the SSM/I sensor, which was first flown in the 1980s and has since been joined by a number of other systems (AMSU, TMI etc.; see previous section)

Of these two approaches, microwave techniques generally provide more accurate estimates of precipitation but less frequently and at a lower spatial resolution. For a given location on the ground, the best temporal and spatial resolutions currently achieved are typically 15 min/4 km for geostationary satellite-based precipitation products and 3-6 h/15 km for passive microwave-based products (Vasiloff et al. 2007). However, the performance depends on a number of factors, including the choice of sensors, the signal processing algorithms used, and atmospheric conditions (e.g. Sorooshian et al. 2011).

Regarding signal processing, a wide variety of techniques has been developed, including physically-based, conceptual and data-driven methods, used either alone or in combination. Combined, merged or 'data fusion' products are also increasingly available which combine the strengths of different approaches. Typically these take advantage of the higher frequency of geostationary observations and the greater accuracy of polar-orbit based observations (e.g. Heinemann et al. 2002; Huffman et al. 2007; Kidd et al. 2008; Box 2.3). For example, one widely used approach is to use cloud tracking or advection schemes based on geostationary observations to 'infill' missing periods in microwave-based observations (e.g. Joyce et al. 2004).

Some algorithms also make use of the outputs from atmospheric models, such as for the wind field and relative humidity (e.g. Scofield and Kuligowski 2003). Products have also been developed which combine satellite observations and real-time or recent raingauge observations (e.g. Xie and Arkin 1996; Tian et al. 2010). In research studies, the TRMM space-borne precipitation radar has also proved to be a valuable tool for evaluation and real-time calibration of microwave-based satellite precipitation products.

With each new generation of satellite, additional techniques are developed to make use of the improvements in accuracy and resolution which become available, and some current research priorities include (e.g. Turk et al. 2008; Sorooshian et al. 2011):

- Quantification of the uncertainty in individual sensors and precipitation products
- Optimization of algorithms for different climate regions, storm regimes, surface conditions, seasons, and altitudes
- Further development of performance metrics

To help to provide a focus for this development work, the International Precipitation Working Group was established in 2001 (Turk et al. 2008). Since 2003, one activity has included routine reporting of comparisons with raingauge and weather radar observations for locations in several regions, including parts of Australia, Europe, South America, Japan and the USA. For example, one finding based on comparisons of nine satellite precipitation products and the outputs from four Numerical Weather Prediction (NWP) models (Ebert et al. 2007) was that, for daily values over land at ~25 km spatial scales:

> Satellite estimates of rainfall occurrence and amount are most accurate during summer and at lower latitudes, while the NWP models show greatest skill during winter and at higher latitudes. Generally speaking, the more the precipitation regime tends toward deep convection, the more (less) accurate the satellite (model) estimates are.

2.5 Multi-sensor Precipitation Estimates

When precipitation measurements are available from several observation systems then a logical next step is to combine the best features from each approach into a single estimate. In weather radar research, products of this type are often called Multi-sensor Precipitation Estimates (MPE) whilst the term High Resolution Precipitation Product (HRPP) is also used in satellite-based applications. The terms multi-parameter, multi-sensor fusion, blending, multisource or data fusion are also used.

The generation of this type of product has been a topic for research for many years with many operational applications appearing in the past one to two decades. The impetus for development has arisen from several directions with many aspects in common, including the following examples:

- Nowcasting – the blending of weather radar, raingauge, satellite, lightning detection and other real-time observations to provide an initial precipitation, cloud and visibility analysis for use in short-range weather forecasting, sometimes guided by the outputs from Numerical Weather Prediction models; see Sect. 4.3 (e.g. Golding 1998; Wilson 2004)
- Satellite Precipitation Estimates – the use of both geostationary and polar-orbiting satellite observations, sometimes including real-time raingauge and weather radar observations where these are available, and making use of the outputs from Numerical Weather Prediction models; see Sect. 2.4 (e.g. Xie and Arkin 1996; Scofield and Kuligowski 2003; Turk et al. 2008)
- Weather radar – the long-established use of real-time raingauge observations to adjust radar rainfall observations, more recently making use of satellite and other types of observations and Numerical Weather Prediction model outputs for the quality control of outputs and infilling of areas with poor coverage; see Sect. 2.3 (e.g. Wilson and Brandes 1979; Zhang et al. 2011)

More generally, the use of multiple sources of observations in the data assimilation process has been routine since the outset for Numerical Weather Prediction models. However, as discussed in Chaps. 4 and 12, in recent years the increasing use of higher resolution convective-scale and mesoscale models has led to the need to consider a wider range of observation systems (e.g. Dabberdt et al. 2005).

Table 2.4 provides some examples of the types of observations which could potentially be included in a multi-sensor precipitation product. In a multi-sensor approach, the aim is typically to use sensors which either provide direct estimates of precipitation, or clues to the presence of precipitation or rain-bearing storms. For example, visible and infrared observations from satellites can show whether a given pixel contains cloud of a type likely to generate rainfall, whilst lightning observations often indicate the presence of convective activity, such as thunderstorms. Numerical Weather Prediction model outputs also provide useful information on atmospheric conditions at different elevations and the extent of cloud and precipitation. Many of the examples shown in the table are candidates for use in a multi-sensor approach and Box 2.3 describes one system which combines several of these types of inputs: the National Mosaic and Multi-sensor QPE (NMQ) System in the USA.

Table 2.4 Some examples of the types of observations which could be used in multi-sensor precipitation estimates, in addition to raingauge, weather radar and satellite observations

Technique	Description
Aircraft- and ship-borne instruments	Automated equipment for monitoring key atmospheric parameters, for transmission by radio or satellite telemetry. For example, aircraft typically report on wind speed and direction, air temperature, altitude, a measure of turbulence and the aircraft position. In some countries (e.g. the USA) this approach has been extended to include turboprop aircraft which typically operate at lower altitudes than jet aircraft. Several thousand aircraft and ships are included in these long-established voluntary programmes (World Meteorological Organisation 2007)
Ground-based GPS	The use of ground-based Global Positioning System receivers in conjunction with surface air pressure observations to estimate the atmospheric precipitable water or integrated water vapour. The estimates are based on the time delay of the signal between satellite and ground, expressed in terms of ionospheric or hydrostatic and 'wet' or water vapour related components. This technique is useful both to assist with thunderstorm forecasting and data assimilation in atmospheric models and has been increasingly used by meteorological services since the 1990s (e.g. Fig. 12.1)
Lightning detection systems	Ground-based networks for detecting the locations of cloud-to-ground lightning flashes, typically inferred from the differences in time of travel to each sensor of electromagnetic waves in the lower atmosphere. These low-frequency emissions sometimes propagate for hundreds of kilometers. These observations are increasingly used as part of the data assimilation process in atmospheric models and in thunderstorm forecasting (see Chap. 4)
Radiosondes	Expendable air pressure, air temperature and humidity sensors for providing vertical profiles within the atmosphere, launched on helium-filled weather balloons and typically using a radio transmitter to relay data. Approximately 1,000 are launched twice each day internationally as part of a coordinated effort within the WMO World Weather Watch Programme and heights of up to 20–35 km are reached. Rawinsondes also provide information on wind speed and direction
Weather Stations	Automatic or manually operated sites typically combining air temperature, air pressure, wind speed, wind direction, humidity, solar radiation, rainfall and (sometimes) other sensors, such as for soil temperature and snow cover. Synoptic stations usually record other parameters such as visibility, cloud cover, present weather and cloud-base. Instruments are mainly operated from land-based locations (including airports and meteorological stations), ocean buoys and oil and gas platforms. Smaller instruments incorporating mainly solid-state sensors are widely used in road weather information systems
Wind profilers	Ground-based vertically-pointing UHF and other radar-based instruments for continuously measuring the vertical wind profile in the lower atmosphere, and sometimes equipped with radio-acoustic sounding systems for estimating air temperature profiles. For example, in one widely used approach, wind speeds at different levels are deduced from the frequency shifts and time of travel for several beams transmitted vertically and at an angle to the vertical resulting from backscattering due to variations in refractivity. Profilers provide the advantage of continuous monitoring of wind speed and, in some cases, air temperature profiles, and have been widely used since the 1990s (e.g. Fig. 12.1)

As for weather radar and satellite observations, it is important to understand the uncertainty in outputs, both for the final multi-sensor product and the individual inputs which are used. The general approaches which are under development are similar to those described in Box 2.2 for weather radar observations with the results presented as quality indices, ensemble outputs, and error covariance matrices. Again, to assess the performance for extreme events, it is often desirable to perform a reanalysis exercise using the present operational configuration of sensors and algorithms (e.g. Nelson et al. 2010). However, it is worth noting that if Numerical Weather Prediction model outputs are used in the product generation process then – as discussed in Chap. 4 – this can be a considerable undertaking.

Box 2.3 NMQ Multi-sensor Precipitation Estimates, USA

Weather radar, satellite and raingauge observations provide estimates for precipitation at different temporal and spatial scales and to varying degrees of accuracy. To help to overcome these limitations, multi-sensor products aim to build on the strengths of each measurement system and to infill any gaps in coverage. The outputs from Numerical Weather Prediction models can also assist with the interpretation of observations and spatial interpolation of data.

For more than a decade, the various NOAA agencies involved in developing multi-sensor precipitation estimates have been combining their efforts to develop a suite of operational products. These include Quantitative Precipitation Estimation (QPE) products for applications such as flash flood warning and water resources management and 3-D radar mosaic tools to assist in severe weather detection, aviation applications and data assimilation for atmospheric models. Contributors include the National Severe Storms Laboratory (NSSL), the Office of Hydrologic Development (NWS/OHD), and the Office of Climate, Water, and Weather Services, together with the Federal Aviation Administration (FAA) and the Central Weather Bureau of Taiwan.

The overall programme is called the National Mosaic and Multi-sensor QPE (NMQ) System (Zhang et al. 2011). Some necessary capabilities which have been identified include (Vasiloff et al. 2007):

- real-time processing of radar, rain/snow gauge, satellite, lightning, and NWP output data
- quality control tools for input datasets
- variable resolution and formatting of input data and output products
- long-term retrospective analysis, that is, reanalysis
- robust verification and assessment tools
- integration of externally derived precipitation products
- high-bandwidth servers for product generation and dissemination

(continued)

Box 2.3 (continued)

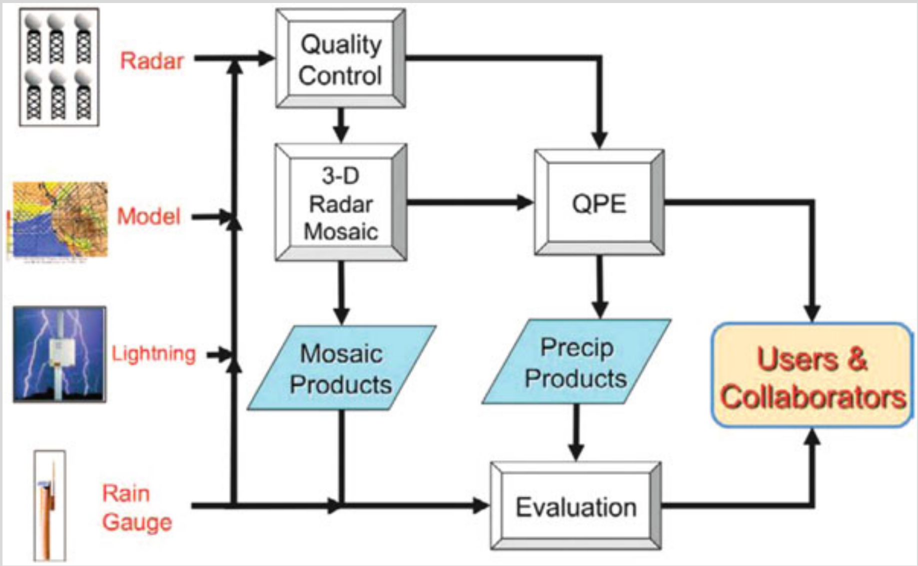

Fig. 2.8 An overview flowchart of the NMQ system illustrating some of the key inputs (Zhang et al. 2011)

Since 2006, experimental products have been generated with a 1 km horizontal resolution and 2.5 min (formerly 5 min) update cycle. These are distributed via a publicly available website (http://nmq.ou.edu/) and directly to key users, and a rolling 3-year archive is also available on-line. The outputs cover the continental regions of the USA, excluding Alaska and off-shore territories.

Since 2007, the NMQ precipitation outputs have also been provided to National Weather Service River Forecasting Centers (RFCs) in parallel with products from the existing Multi-sensor Precipitation Estimator (MPE). From an operational perspective, in addition to including new data sources and algorithms, more use is also made of automation for the initial data quality control, gap-filling and blending of sources. As part of the development programme, extensive comparisons have also been performed both with other precipitation estimators and with the outputs when used with distributed rainfall-runoff models (e.g. Kitzmiller et al. 2011).

The types of real-time observations which feed into the system change as technological developments occur but the main inputs include (Fig. 2.8):

- A quality-controlled three dimensional (3-D) reflectivity mosaic at a grid scale of approximately 1 km for 31 vertical levels derived from more than 140 of the S-Band NEXRAD WSR-88D weather radars operated in the USA and from the Environment Canada network of 31 C-band radars

(continued)

Box 2.3 (continued)

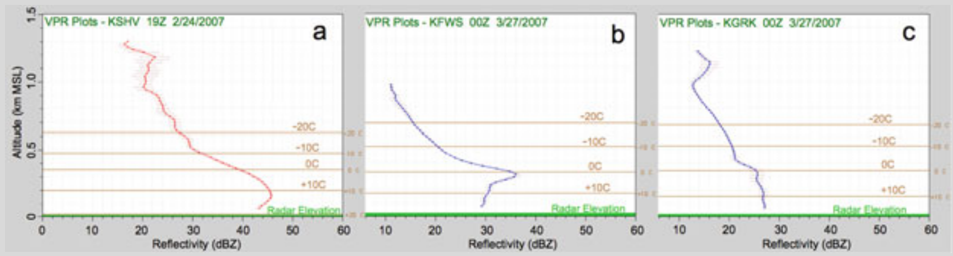

Fig. 2.9 Examples of Vertical Profiles of Reflectivity (VPRs) for (**a**) convective, (**b**) stratiform and (**c**) tropical precipitation. The *horizontal lines* indicate, from *top to bottom*, −20, −10, 0, and 10 °C temperature heights at the radar sites. Some features suggested in the profiles include (**a**) a region with coalescent growth of large rain droplets and possibly hail stones immediately above cloud base at ~1,500 m (**b**) a bright-band feature near the freezing level and (**c**) continued growth towards the ground of a large amount of medium sized raindrops in a very moist environment (Zhang et al. 2011)

- Ground-based observations from several thousand raingauges transmitted via Data Collection Platforms to the GOES East and GOES West geostationary satellites for initial processing by the Hydrometeorological Automated Data System HADS (http://www.weather.gov/oh/hads/WhatIsHADS.html)
- Short-range forecasts from the NOAA/NCEP Rapid Update Cycle/Rapid Refresh atmospheric model which has a 13 km grid scale at 50 vertical levels and is updated every hour from 1 to 18 h ahead (Benjamin et al. 2004, http://rapidrefresh.noaa.gov/)

Several other types of observation are also ingested, including lightning observations and data from selected Terminal Doppler Weather Radars and television station radars.

The multi-sensor products are derived by automatically comparing and combining outputs from these individual systems. For example, estimates for the probability of severe hail and the maximum hail size are derived primarily from the 3-D radar reflectivity and model-derived air temperature analyses.

For flash flood forecasting, one key component of the overall system is the next-generation QPE (Q2) suite of tools, which derive best estimates for the types and intensity of precipitation. This includes an automated precipitation classification scheme which is based on information from the 3-D reflectivity mosaic, the model outputs, and lightning, surface air temperature and moisture observations. The algorithm distinguishes at a pixel scale between stratiform, convective and warm rain, hail and snow and then applies an adaptive reflectivity relationship appropriate to the type of precipitation. Vertical profile of reflectivity corrections are also applied (e.g. Fig. 2.9).

(continued)

Box 2.3 (continued)

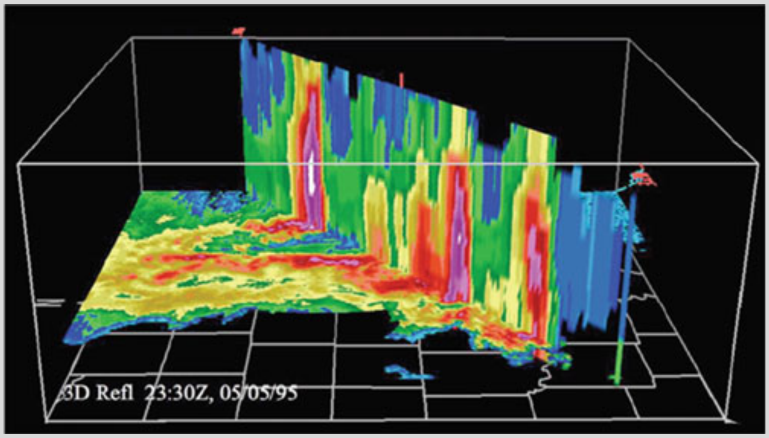

Fig. 2.10 Horizontal and vertical cross-sections from the 3-D reflectivity mosaic of a hail storm in Dallas on 5 May 1995 (Zhang et al. 2011)

For example, the procedure used to distinguish between convective and stratiform rain makes use of threshold values of reflectivity, the detection of one or more cloud-to-ground lightning flashes in the vicinity of the pixel within the last 5 min, and vertical profiles of air temperature from the atmospheric model (Zhang et al. 2011).

Some other Q2 products include raingauge-adjusted radar rainfall outputs, produced using an inverse-distance weighting scheme and – for the western USA – the 'Mountain Mapper' raingauge product which is derived using a high-resolution reference precipitation climatology (Daly et al. 1994; Schaake et al. 2004). Where raingauge values are used, these are first checked using a suite of validation tools which search for anomalous values and reject those that seem implausible.

In total, approximately 20 products are available. Some other examples include real-time assessments of weather radar coverage and quality and cross sections of 3-D reflectivity for any user defined cross section across the USA and southern Canada (e.g. Fig. 2.10).

The NMQ system and website also includes a suite of real-time verification outputs, based on comparisons with telemetry observations from local and regional raingauge networks and manually recorded values provided by the extensive national voluntary observer network (e.g. Fig. 2.11; see also http://www.cocorahs.org/). Outputs from other systems are also available for comparison, such as the satellite-based Hydro-Estimator product (Scofield and Kuligowski 2003).

The statistics which are reported include the bias, correlation coefficient and root mean squared error, with outputs provided on a map, tabulated and graphical basis. One particular focus for validation is the western USA

(continued)

Box 2.3 (continued)

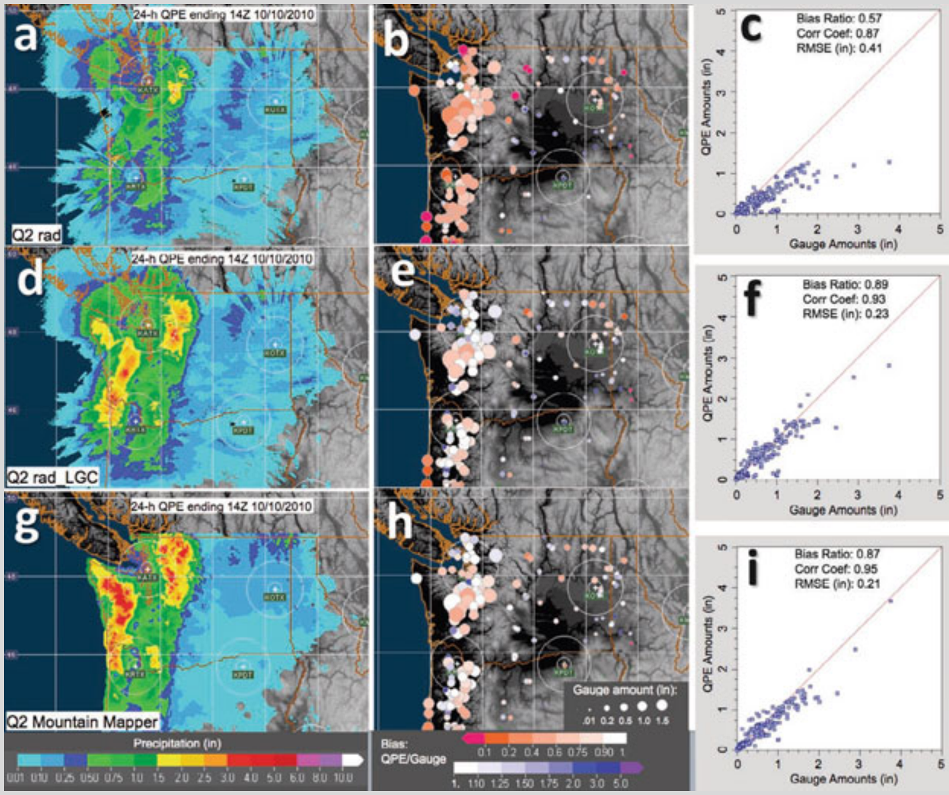

Fig. 2.11 24-h accumulations of precipitation estimates in the Pacific-Northwest region for the period ending at 1400 UTC on 10 October 2011 (**a**) Q2 radar (**d**) Q2 radar with local raingauge correction and (**c**) Q2 raingauge-only Mountain Mapper. The bubble charts (**b**, **e**, and **h**) show the bias ratios between the three different Q2 products and manually-recorded (CoCoRaHS) raingauge observations, where the circle size represents gauge-observed amount and the intensity of shading represents the Q2/gauge bias. The scatter plots (**c**, **f**, and **i**) show the correlation between the Q2 estimated and raingauge-observed amounts. Similar plots for other types of rainfall (e.g. convective) and/or in other parts of the USA (e.g. the southwestern USA) often show better performance for the Q2 radar-raingauge product (Zhang et al. 2011)

where, due to the mountainous terrain, there are significant gaps in radar coverage (e.g. Fig. 2.6 – see main text).

Some current areas for research include how best to use space-borne radar observations of precipitation from the TRMM satellite and its successor (GPM), improvements to hydrometeor identification and radar data quality control using dual polarisation outputs, the use of gap-filling X-band and mobile C-band radars, and the development of techniques to quantify the uncertainty associated with each product. More generally, the community-wide approach which is being adopted easily allows researchers access to data and provides a ready-made validation framework for the evaluation of new techniques as these become available.

2.6 Summary

- Raingauges provide direct measurements of rainfall at a single location. Tipping bucket gauges are perhaps the most widely used recording type, although weighing gauges and solid state instruments are increasingly used. When a network of gauges is available, catchment-wide and other spatial estimates are typically derived using weighting or surface-fitting approaches, with the accuracy of the estimates dependent on the density of the gauge network, topography, typical storm types and scales, and a range of other factors
- Weather radar networks are used in many countries although – due to the expense – the coverage is limited in some parts of the world. The accuracy of outputs continues to improve with Doppler techniques introduced in the 1990s and dual polarisation methods recently adopted in several countries. The spatial view of precipitation makes radar a useful complement to raingauge observations although with some assumptions needed to estimate values at the ground surface and to compensate for other sources of error. C- and S-band devices are generally used in national networks although shorter range X-band radars are increasingly used for gap-filling and in flash flood and other applications
- The complementary nature of raingauge and weather radar observations has led to the widespread use of raingauge adjustment schemes for radar outputs. In recent years, this approach has been extended to make use of other sources of real-time information, such as the outputs from Numerical Weather Prediction models and satellite and lightning observations. The resulting outputs increasingly include quality indices or ensemble estimates for the uncertainty
- Satellite precipitation algorithms provide a spatial estimate of rainfall but usually at a coarser spatial resolution and less frequent intervals than for weather radar. A number of products are available using a wide range of techniques and sources of real-time information. Increasingly these combine the visible and infrared observations from geostationary satellites with the microwave observations from polar orbiting satellites, in some cases guided by the outputs from Numerical Weather Prediction models
- In recent years, multi-sensor precipitation products have started to become available operationally and have great potential for flash flood (and other) applications. These are not tied specifically to any one observation system and aim to provide a best estimate of current precipitation from a wide range of sources together with an estimate for the uncertainty in the outputs
- For individual measurement systems, there are many guidelines and standards available. International intercomparison studies have also been performed for raingauges, weather radar products, and satellite precipitation estimates. These allow users to compare the performance of equipment and algorithms for different storm types and climatic regions, and in some cases – such as for satellite precipitation estimates – to view regular near real-time updates to results on a project website
- Some current research themes which are likely to benefit flash flood applications include the provision of real-time uncertainty estimates for all types of approach,

the increasing use (and understanding) of dual polarisation weather radar outputs, and improvements to the resolution and accuracy of satellite-based precipitation estimates. For the future, the outputs from the international Global Precipitation Mission (GPM) are likely to be of particular interest for flash flood applications.

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Chapter 3
Catchment Monitoring

Abstract During flash floods, river gauges are widely used to determine when river levels exceed threshold values, and to provide inputs to flood forecasting models. Ground-based or satellite observations of soil moisture or snow cover are sometimes also required. To estimate flows, river levels are typically converted to flows using a stage-discharge relationship; alternatively velocity measurements can be made using ultrasonic or electromagnetic gauges. For monitoring snow and soil moisture conditions, many different methods are used, although with spatial sampling issues for ground-based observations and accuracy and spatial resolution issues for satellite-based methods. These topics are discussed in this chapter, together with gauge siting considerations and some of the supporting technologies required for observation networks, such as telemetry and information systems.

Keywords River level • River flow • Stage-discharge relationship • Catchment conditions • Soil moisture • Snow conditions • Telemetry • Information systems • Gauge siting

3.1 Introduction

Observations of river conditions are a key input to many flash flood forecasting and warning systems. Information on soil moisture or snow conditions is also required in some situations. Due to the speed at which events develop, a key challenge is to pass the required information to decision-makers in time to be useful. Usually this requires the use of a telemetry system to relay observations together with associated data processing and analysis tools. However, manual observations have a valuable role to play as a backup in case of gauge or telemetry failure and for reporting on event-specific factors such as debris blockages. Indeed, in some catchments, observers are the main source of information where there is little or no automated instrumentation. Similar principles apply to other types of flash flood, such as dam breaks, ice-jam floods and debris flows.

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This chapter provides an introduction to these techniques and to the related topics of telemetry and information systems. Gauge siting issues are also briefly considered. Although many of these techniques are applicable to all types of flash flood, the focus is on river flooding. Later chapters then consider methods specific to other types of flood, such as the use of geophones for debris flows (Chap. 9), differential pressure transducers for surface water flooding (Chap. 10), and piezometers for dam breaks (Chap. 11). Chapter 12 also discusses several recently developed monitoring techniques which show potential for use in flash flood warning applications, such as large-scale particle image velocimetry (LSPIV) and wireless sensor networks. As with precipitation monitoring techniques (see Chap. 2), some common themes throughout include the performance and resilience of instruments in extreme conditions and techniques for quantifying the uncertainty in sensor outputs.

3.2 River Monitoring

3.2.1 River Levels

River level observations are a key input to many flash flood warning systems. For example, warnings are typically issued when levels exceed a critical threshold either at the location at risk or – to provide additional lead time – at a gauge further upstream (see Chaps. 9, 10, 11). Simple correlation models are also widely used to relate levels at one site to those at another (see Chap. 5). Also, as discussed in the next section, levels can be converted to flows if a suitable stage-discharge relationship is available; for example for input to a real-time flood forecasting model.

The science of monitoring river levels and flows (and other elements of the hydrological cycle) is called hydrometry and – in the early days – level measurements were typically made by observers recording readings from graduated painted metal ‘staff gauges’. In some locations, including some community-based flash flood warning systems, these manual approaches are still the primary method used, with observations typically relayed to colleagues by cell phone or hand-held radio. When budgets are a constraint, scales painted onto bridges and other structures using waterproof paint provide another less robust option.

For flash flood warning applications, some possible limitations include the time taken for observers to reach gauges (unless resident on site) and potential safety issues during flood events, particularly at night and when flooding is widespread. However, as discussed in later chapters even in the most sophisticated systems observations by staff and volunteer observers are useful both as a backup in case of telemetry or instrument failure and to provide additional information on flooding conditions. More generally, regular site visits for checks and maintenance remain essential.

Historically, one of the first approaches to automatically recording river levels was to use clockwork-driven chart recorders. Then, as telecommunication systems improved, data loggers combined with landline, cellular, radio, meteor burst or satellite-based telemetry were increasingly adopted. Outputs are typically provided either at fixed intervals (e.g. every 15 min) or once critical thresholds are exceeded. For continuous

Table 3.1 Summary of some widely used techniques for monitoring water levels in rivers, reservoirs and other water bodies

Type	Principle of operation	Some operational considerations
Bubbler or pneumatic	Release of compressed air or nitrogen through a submerged nozzle; the water depth is then inferred from the operating pressure (e.g. Fig. 3.4)	Requires a small pump or compressor or regular recharge of a compressed gas cylinder. The gas supply line to the nozzle can be vulnerable to damage by debris or blockage by sediment
Float-in-stilling-well	A float suspended by wire or tape from a pulley; the water depth is then inferred from the number of turns of the pulley. The float is typically installed inside a stilling well suspended in the water or in a downshaft in the river bank connected to the water by an underground pipe or culvert (e.g. Fig. 3.4)	There is a risk of the float jamming and the wire or tape breaking or dropping off the pulley. There are sometimes access and confined space working issues with stilling wells and downshafts, and the risk of blockages by debris or sediment. The maximum level which can be recorded is limited by the elevation of the pulley
Pressure transducer	A solid-state submerged pressure sensing device, with the depth proportional to the pressure recorded (e.g. Fig. 3.1)	The electrical cable to the sensor is potentially vulnerable to damage. Sensors used to have a relatively short operating life in the early days although are now hugely improved
Ultrasonic or radar	Downward-looking ‘non-contact’ devices mounted on a bridge or mast; the level and hence the depth is then inferred from the time of travel for the reflected signal (e.g. Fig. 6.3)	The reflected signal may be degraded or interrupted by debris on the water surface and other factors; ultrasonic gauges require air temperature corrections

recording, float-in-stilling-well devices were one of the first approaches to be used and Table 3.1 summarises the basis of that approach and some other widely used techniques. Many of these methods are also suitable for use in other applications where measurements of levels are required, such as in reservoirs, lakes, estuaries and coastal regions. The operational considerations listed are an indication of some of the maintenance and other issues which sometimes arise; however in many cases these can be mitigated through good design and well-defined operating procedures.

In addition, video and webcam installations are widely used on rivers and watercourses in urban areas to help to identify where flooding is occurring and to check for issues with debris at bridges, trash-screens and other structures (see Chap. 10). If a staff gauge is in view then it may also be possible to read approximate values from the images. Another option is to use simple ‘on-off’ float or electrode devices to detect when levels reach a pre-defined value; for example as a ‘last resort’ for issuing a warning if all other systems have failed. However, as discussed in Chap. 6 there are some issues to consider with this approach regarding the risks from missed warnings and false alarms.

For all types of gauge, in addition to the risks from debris and sediment, during flood events there is a possibility that the data logger and any telemetry equipment will be flooded. However, this is normally avoided except in extreme events by raising

Fig. 3.1 Example in the UK of a pressure transducer river level gauge and data logger housing

or relocating key equipment above estimated flood levels. For example, in the U.S. Geological Survey, the aim in this process – called flood-hardening – is for all river gauges to be resilient to an estimated 1 in 200 year return period level (See Box 3.1). Another factor to consider in reviews of this type is whether the recording range of the gauge is sufficient for it to continue operating at extreme levels.

To increase resilience, backup instruments are sometimes installed in high risk locations such as city centres, and warning and forecasting systems are normally designed to be resilient to the loss of individual instruments, as discussed in later chapters. Where debris is a serious issue, non-contact gauges are increasingly used; for example in debris flow warning systems (see Chap. 9). More generally, it is important to routinely check gauge datum levels relative to local or national benchmarks since values occasionally change; for example when gauges are repaired or replaced. Accurate datum values are also required when river levels are used in hydrodynamic flood forecasting and flood risk mapping models of the types described in Chaps. 5 and 8. Also, due to land degradation, sedimentation is an increasing problem in many countries and smaller flash flood prone tributaries are particularly vulnerable. For example, increases in river bed levels of a metre or more per decade or more are a possibility, in some cases requiring regular resurveys of flood warning threshold levels and even relocation of gauges.

3.2.2 *River Flows*

In some applications, measurements of river flows are more useful than values for levels. This then allows the water balance in a river or catchment to be estimated, and flood forecasting models to be developed based on the principles of conservation of mass and (possibly) momentum (see Chap. 5).

Fig. 3.2 Low flow gauging with a current meter (*left*) and an acoustic Doppler used to record measurements on Wild Rice River, North Dakota during 2010 flood (*right*; U.S. Geological Survey/ photo by Don Becker http://gallery.usgs.gov/)

There are two main approaches to the automated measurement of flows. These are to measure levels continuously and then to apply an empirical stage-discharge relationship (or rating curve), or to measure the water velocity and from that deduce the flow (e.g. Herschy 1999; Boiten 2008; World Meteorological Organisation 2010). The first method relies on occasional manual observations of discharge (or 'spot gaugings') to define the relationship with levels whilst the second is generally considerably more expensive in terms of the initial investment required but provides a more direct estimate for flows. Various combinations of these techniques are also used, as discussed later.

Historically, the main approach used to measure discharges manually was to use a current or velocity meter. This would be suspended by a cable from a mobile frame on a bridge or a cableway across the river, or attached to a rod when levels were low enough for wading (e.g. Fig. 3.2). This approach is still widely used and the basis of the technique is that velocities and flow depths are recorded at a number of locations across the river, with the velocity measurements typically made at one or two depths each time. The resulting values are then integrated across the cross section to provide an estimate for the average discharge at the time of the site visit. Allowances are often made for factors such as the drag on the suspension cable and the changes in river level whilst the observations are being made.

Using this approach, measurements are typically made at regular intervals, such as every month, and during major flood events. This then allows a stage-discharge relationship to be developed by fitting a rating curve to the resulting spot gaugings. Figure 3.3 illustrates some of the issues which often arise at high flows, assuming a power law relationship which is by far the most widely used approach, although polynomial functions are occasionally used (e.g. ISO 1996, 2010). For simplicity, in the figure it is assumed that the zero stage and discharge values coincide, which is often not the case.

In recent years, current meters have increasingly been replaced by Acoustic Doppler Current Profiler (ADCP) devices. These provide estimates of velocities from the changes in frequency (or phase) in an ultrasound signal reflected from particles in the water and are generally quicker and safer to operate; for example, with no submerged cables to snag debris. In addition, flow estimates are

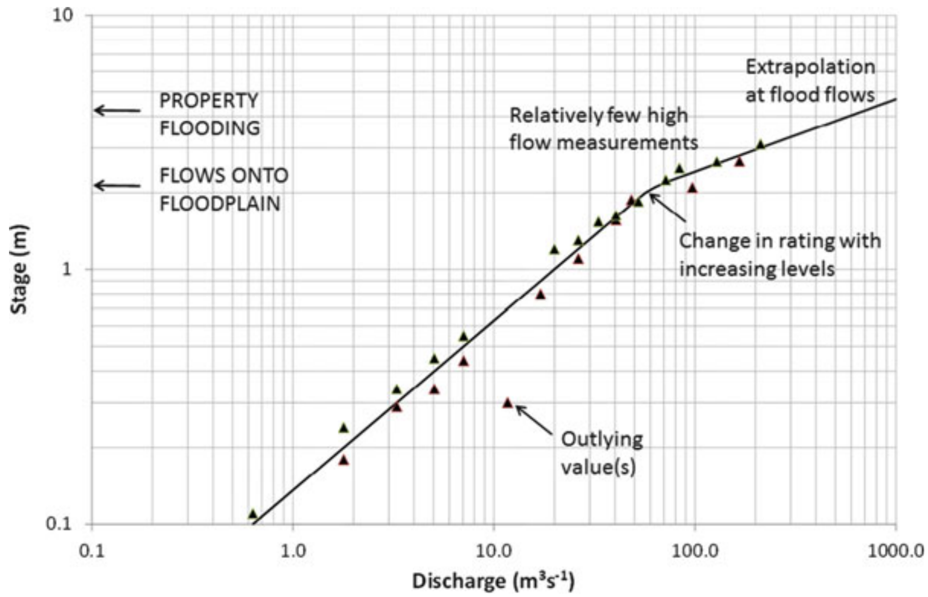

Fig. 3.3 Illustration of a stage-discharge relationship and some of the calibration issues which arise, particularly for high flows

generally more accurate, particularly in unsteady and recirculating flows. The instrument is typically mounted on a floating platform or boat and this is then traversed across the river to provide a continuous read-out of depth and velocity. The resulting values are then integrated automatically to provide an estimate of the flow.

Another technique which is occasionally used is dilution gauging. With this approach, a chemical tracer – such as a salt or dye – is added to a river at an upstream location and the variations in concentration are recorded further downstream. This then allows the flow to be estimated from a theoretical relationship. However, this approach is more suited to low to medium flows than to flood flows. As discussed in Chap. 12, radar and imaging techniques also show promise for measuring surface velocities during flash flood events, and hence for deriving estimates for the flow.

Despite these advances, stage-discharge relationships remain widely used, although have a number of limitations. For example, river channel cross sections frequently change over time due to erosion and sedimentation, affecting the relationship between stage and discharge, and this effect is perhaps most likely to occur during flood events. Also, at some locations the relationship may be temporarily affected by backwater influences from locations further downstream, such as unusually high tributary inflows, tidal influences, and control structure operations. At some gauges, a hysteresis (or 'loop rating' effect) occurs due to the discharge being higher – for a given level – on the rising limb of the hydrograph than on the recession. Again, these effects are sometimes only a factor in flood conditions and have the potential to lead to large over- or under-estimates of flows. Other factors which sometimes need to be considered include river ice, dredging or vegetation growth.

The need to take measurements during flood events also has potential safety implications for staff and in some cases sites are inaccessible due to flood waters, although making measurements some way up- or downstream at a safer location may be an option. Also, for rivers with a floodplain, the form of the relationship sometimes changes dramatically once flows go out of bank, as illustrated in Fig. 3.3. This then ideally requires measurements of flows both in the river channel and on the floodplain. For flash flood prone rivers, another consideration is that, due to the fast response, it is often a challenge for personnel to reach sites in time to record the highest flows. Gauging at night is a particular risk and – if performed – requires spot lights and more rigorous risk assessments and safety procedures.

In practice therefore, on flash flood prone rivers, there may be few opportunities to take high-flow measurements to define the upper end of the stage-discharge relationship. Rating curves are therefore often extended at high flows using linear extrapolation (in logarithmic coordinates), or using hydraulic formulae; for example as part of a conveyance-slope approach (e.g. World Meteorological Organisation 2010). However, another possibility is to estimate high flows using a hydrodynamic model. For example, 1D and/or 2-D hydraulic models are increasingly used to guide the form of the extrapolation, and to estimate preliminary rating curves for newly installed gauges. Typically, for a model to be developed, the river channel and floodplain need to be surveyed over a distance which is sufficient to define the hydraulic behavior of the river reach. A cautionary note though is that some spot gaugings are still ideally required to calibrate the model, and if these are not available there can be considerable errors in the results.

In some cases, it may also be possible to derive approximate estimates for peak flood flows based on post-event survey data and hydraulic models or formulae. Typically peak levels are estimated at several points along a river reach from trash marks, debris, vegetation damage and other clues. In high risk locations, another option is to install instruments to record peak levels in future events. For example, one cheap and widely used type of maximum water level (or crest-stage) recorder consists of a metal tube containing a cork which floats upwards as levels rise and then – due to expansion of the cork - jams in place at the highest level reached.

More generally, when using stage-discharge relationships, there are many techniques for estimating the uncertainty both in individual discharge measurements and in the flows estimated from the curve (e.g. ISO 2010; World Meteorological Organisation 2010). Typically these rely on estimating confidence limits assuming a Gaussian (Normal) distribution for the errors in transformed coordinates, whilst other possibilities include error decomposition, Monte Carlo, and Bayesian techniques (e.g. Sauer and Meyer 1992; Pappenberger et al. 2006; Petersen-Øverleir et al. 2008). However, when there are uncertainties about the high flow end of a rating curve, many hydrometric services specify an upper limit for the computed flows and include a warning flag with higher values, or simply truncate values beyond that point. These are both important factors to consider when developing flood risk mapping and flood forecasting models.

Due to the issues with stage-discharge relationships, automatic flow recording devices have many potential advantages. However, cost is often a limiting factor which tends to restrict their use to higher risk locations or key gauging stations. For example, one approach is to install a purpose-made gauging structure in which the flow geometry is well understood thereby allowing a theoretical level-flow relationship to be calculated, Usually this is then checked using a few initial spot gauging measurements and occasional measurements thereafter. Some examples include thin-plate weirs, Crump weirs, and broad-crested weirs. Depending on the type of structure, the optimum monitoring location for levels is typically either at or shortly upstream of the crest or downstream face. In some cases, it is possible to use existing river structures such as weirs; however, a hydraulic modeling study may be required to define the stage-discharge relationship to use. Also, for critical locations, physical model tests are occasionally justified, using scale models in a hydraulic laboratory.

However, for any type of structure, unless it has been designed specifically for high flows, there is a risk that it will be drowned (i.e. become 'non-modular') or bypassed in flood conditions. Other influences may also come into play, such as from bridge decks or pipe crossings. These factors all potentially affect the relationships between levels and flows and, again, hydraulic or physical modeling is sometimes used to better define the high flow performance. Also, corrections for non-modular flows can often be made by using observations from a second water level telemetry gauge installed downstream of the structure.

Another option for continuous flow monitoring is to use permanently installed ultrasonic (hydroacoustic) or electromagnetic recorders. For example, one approach is to install ultrasonic transmitters and receivers at several depths in a river bank. The resulting velocities are then integrated to provide an estimate for the total flow across the cross-section. The calculations are then repeated as often as required (e.g. every 15 min). Alternatively a simpler approach, requiring a smaller-scale installation, is to use one or more side-looking or bed-mounted devices to record the velocity at one or more locations. The flow is then estimated from a regression ('velocity-index') relationship between mean cross-section velocities and the index values, and a stage-area relationship based on survey data or other techniques. Although this still requires making ADCP or current meter measurements to derive the relationship, compared to a stage-discharge relationship some advantages include a more robust relationship, not affected by some of the factors discussed earlier, and the ability to handle backwater influences. Another approach, which is less widely used, is to place an electromagnetic coil device in the river bed, with electrodes to receive the signal in the river bank; the principle of operation being that the magnetic field detected varies depending on the flow velocity.

However, for all of these techniques, it is still desirable to make occasional spot gaugings to check the calibration of the instrument. For example, over time the performance may be affected by factors such as erosion, vegetation growth and sedimentation both at sensors, and in the river channel or structure. There are also usually practical limits on the width of river cross section which can be monitored, whereas in principle it is possible to estimate a stage-discharge relationship for any river, with perhaps the most famous examples being for the Ganges, Nile and Amazon.

Box 3.1 USGS River Monitoring Network

The United States Geological Survey (USGS) coordinates river level and flow monitoring across the USA (http://water.usgs.gov/). Historical and real-time observations are widely distributed for flood, drought, water resources, recreational and other applications. The observation network is supported by funding through federal water and environmental agencies and approximately 850 state and local funding partners through the USGS Cooperative Water Program. Funding is also provided for a core set of gauges through the USGS National Streamflow Information Program (National Research Council 2004; NHWC 2006).

The first station to be established was in 1889 at Embudo on the Rio Grande in New Mexico and a systematic program of streamflow gauging was started soon after. Measurements in the early days were made by observers taking readings from staff gauges, with discharges measured by current meter. The earliest automated level gauges typically consisted of float-in-stilling-well devices with chart or paper-tape recorders and these were in widespread use by the 1920s, although the recorders were subsequently replaced by electronic data loggers.

Satellite telemetry using the GOES (Geostationary Operational Environmental Satellite) system was introduced in the 1970s and is nowadays the standard approach to transmitting data, although radio and telephone-based (cell phone or land-line) telemetry is used in some locations. Values are typically recorded at 15-min or hourly intervals then transmitted on an hourly or 4-hourly basis, with more frequent intervals under emergency conditions. More than 95% of the network is on telemetry.

Another change in recent years has been to use pressure (pneumatic or bubbler) sensors for most new installations (Fig. 3.4). These have the benefits of lower maintenance requirements, improved performance (particularly in ice), and reduced health and safety issues, avoiding the need to work in confined spaces as with stilling wells. Similarly, ADCP (Acoustic Doppler Current Profiler) devices have largely superseded current meters for measurements of streamflow due to their lower costs and improved accuracy, particularly for unsteady or complex flows.

By 2010, the network consisted of approximately 7,600 stream gauges, 400 lake gauges, 1,300 borehole (well) gauges, and 3,600 precipitation gauges. In recent years, a programme to 'flood-harden' existing gauges has also been initiated to enable them to withstand future flood events. Typically this is done by raising and strengthening the installation or installing a back-up instrument nearby, with minimum elevations based on the estimated levels for a 1 in 200 year return period flood.

For river gauges, both real-time and historic river data can be obtained for more than 3,000 long-term gauges via the WaterWatch website http://water.usgs.gov/waterwatch/, together with a wide range of statistical, graphical

(continued)

Box 3.1 (continued)

Fig. 3.4 USGS pressure sensor on the Lackawanna River at Scranton, Pennsylvania, and float-in-stilling-well gauge on the floodplain at Harrisburg, Pennsylvania

and map-based outputs. Some other recent innovations include the WaterAlert service, research on new approaches to real-time discharge observations, and establishment of a pool of temporary river gauges to deploy during flood events:

- **WaterAlert** This service http://water.usgs.gov/wateralert/ was established in 2010 and allows users to receive daily or hourly notifications from any USGS gauge, based on user-defined threshold values for river level, streamflow, precipitation and/or selected water quality parameters. The service is free-of-charge and is set up by selecting the gauges which are required, the notification interval, and the thresholds to use. Thresholds can be defined for when parameters exceed or drop below a value or fall within a given range. Notifications are then sent by email or text message when these criteria are met. The StreaMail service also allows users to request current river levels and discharges via email or text message to cell phones and other hand-held devices, with typically up to a 5-min delay. Some sites also have voice modems allowing verbal messages to be sent directly to city authorities and other emergency responders when threshold criteria are exceeded.
- **Real-time discharge measurements** The USGS was one of the first organisations to adopt ADCP techniques and the use of hydroacoustic

(continued)

Box 3.1 (continued)

devices remains an active area of research. In recent years, the focus has been to find faster and safer ways to measure river surface velocities and hence discharges in real-time, particularly during flood events or when there is ice cover (Fulton and Ostrowski 2008). Options under evaluation within the research programme include hand-held radars and the use of river bed (upward-looking), bridge or frame mounted ultrasonic devices to provide real-time telemetry of river velocities and streamflows.

- **Rapid deployment gauges** In recent years a pool of rapid deployment river level gauges has been introduced for use during flood and other emergencies, either to provide data where no existing gauges are available or as a temporary replacement for instruments which are out of operation. The gauges are designed to be lightweight and capable of being installed by one person, and include a battery, antenna, solar panel and Data Collection Platform, providing several telemetry options. Some examples of the use of these gauges include deployment during a potential flood threat in the James River Basin in North Dakota in 2009 and in Minnesota in 2010 and 2011 (e.g. Fig. 3.5). In addition to the national pool of instruments, some state authorities have also funded the purchase of locally-available instruments (e.g. North Dakota State Water Commission 2011).

Fig. 3.5 Rapid Deployment Gauge (Version III) deployed to monitor flooding in the Red River Valley at Wolverton Creek near Comstock in Minnesota during flooding in 2010 http://water.usgs.gov/hif/programs/projects/rapid_deployment_gage_III/

3.3 Catchment Conditions

3.3.1 Introduction

In addition to monitoring river levels and flows, in flash flood applications it is often useful to have an indication of the antecedent conditions in a catchment. In particular, the soil moisture can have a significant impact on the flood response. The main exceptions are in arid regions, where factors such as geology and topography are often the main influences on surface runoff, and in some urban areas, where the landscape is heavily modified from natural conditions (see Chap. 10). Also, in colder climates, the influences from snow cover and snowmelt may need to be considered.

Where antecedent conditions are a factor, due to cost it is usually impractical to make direct ground-based measurements except at a few locations. This then leads to sampling issues since distributions of soil moisture and snow cover tend to vary widely due to variations in soil types, vegetation, topography and other factors. Direct measurement techniques are therefore most likely to be representative in flat regions with fairly uniform land cover, such as prairies, low-lying boreal forests and grasslands. For these reasons, empirically-based soil water accounting and snowpack models are perhaps more widely used operationally, using rainfall and weather station observations as the primary inputs. However, for snow cover, remote sensing observations are increasingly used. The following sections discuss some of these techniques in more detail.

3.3.2 Soil Moisture

For monitoring soil moisture at individual locations, several techniques could potentially be used. These include neutron and gamma probes, gravimetric (weighing) techniques, mast-mounted radiometers, heat dissipation sensors, and time and frequency domain reflectometry (dielectric constant/capacitance) approaches. For example, heat dissipation sensors record the temperature difference at the sensor caused by a pulse of heat, whilst time domain approaches typically measure the changes in a microwave signal transmitted between two or more vertical probes (e.g. World Meteorological Organisation 2008, 2009).

Many of these techniques are suitable for continuous monitoring and the transmission of outputs by telemetry. For example, in the USA, the U.S. Department of Agriculture (USDA) operates a national network of more than 100 climate monitoring sites. These include both weather stations and dielectric constant devices for real-time hourly monitoring of soil moisture at a range of depths (Schaefer et al. 2007). Similarly, in Oklahoma, a dense state-wide network is operated which provides real-time observations from more than 100 stations. Values are transmitted at 30 min intervals for one or more depths using heat dissipation sensors (http://www.mesonet.org/; Illston et al. 2008).

However, although these techniques have potential for flash flood applications (see later chapters), soil moisture accounting approaches tend to be used more widely. With this approach, estimates are derived from a water balance which includes rainfall, evaporation and, increasingly, surface runoff components as well. Different land use types and hence evapotranspiration rates are usually considered, and groundwater and other terms are sometimes included.

The real-time inputs typically include telemetered values of rainfall from raingauges or weather radar together with windspeed, humidity, solar radiation and air temperature observations to derive Penman or Penman-Monteith estimates of evaporation (FAO 1998). In some systems, the soil moisture estimates are periodically adjusted (or updated) if values drift too far from estimated conditions 'on-the-ground'. Calculations of this type are typically performed as a regional or national service run by hydrological, agricultural or other agencies.

This approach is also used by some meteorological services and – in some countries – the post-processed soil moisture outputs are made available as a product for use in other applications. For example, in the UK, gridded values at a national scale are available at spatial and temporal scales of 40km/weekly from a two-layer water balance approach and 2km/hourly from a land-surface model (e.g. Blyth 2002). Also, as described in Chap. 8, a continuous soil moisture accounting approach is widely used in flash flood guidance approaches. Indeed, rather than use externally calculated values, many flood forecasting models incorporate a soil moisture accounting component from which saved values are used to initialize the model at the start of every run (see Chap. 5). In some cases, there is also the facility for occasional manual corrections of values, or automated updating based on a surrogate value, such as the current river baseflows. For example, one option for manual updating is to make adjustments at times when the catchment soil moisture state is reasonably well known, such as after a long dry period or a prolonged period of heavy rainfall.

Although evapotranspiration estimates are often a component in these calculations, direct observations of evaporation are rarely used due to the measurement difficulties. For example, evaporation pans are widely used at meteorological stations and consist of open containers which record the depth of water lost in a given period due to evaporation. However, due to heating of the container, rainfall and other factors, the accuracy of the values provided is often poor at least at the timescales required for flood-related studies. More direct techniques are available, but tend to be used more in research studies than operationally; for example, eddy correlation techniques are well-established and infer the flux of water vapour using frequent sampling of humidity and air temperature fluctuations, and horizontal and vertical velocities, at a fixed height above the ground.

For many years, satellite observations have been seen as a possible alternative or supplement to ground-based observations or soil-moisture accounting techniques. Observations are typically made in the infrared or microwave frequencies from polar orbiting satellites, and post-processed to account for different types of land cover and atmospheric influences on the signal (e.g. Alavi et al. 2009). Microwave techniques show the most promise for hydrological applications, and both passive and active (Synthetic Aperture Radar or scatterometer) sensors are used (e.g. Wagner et al. 2007). When these are available, long wavelength (L-band) sensors normally outperform the shorter C-band and X-band wavelengths. For example, L-band signals are little affected by solar illumination, clouds and – to some extent – vegetation so can be used night and day over a wider range of surfaces. The resulting values provide a spatially-averaged estimate for soil moisture in near real-time for soil depths of up to a few centimetres.

One particular system of interest for flood forecasting is the experimental NASA Soil Moisture Active Passive (SMAP) near- polar orbiting mission. This will include an L-band radiometer and high resolution synthetic aperture radar and the resulting emission and backscatter observations will be used to derive products for soil moisture and soil freeze/thaw conditions. The coverage will be global with a full scan completed every 2–3 days with a resolution of approximately 10 km for soil moisture and 2–3 km for freeze-thaw states (http://smap.jpl.nasa.gov/instrument/). This compares with a resolution of approximately 25–50 km provided by the NASA AMSR-E radiometer (2002–2011) (http://weather.msfc.nasa.gov/AMSR/) and 35–50 km for the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission launched in 2009 (http://www.esa.int/).

Some further background information on satellite systems and orbits is provided in Chap. 2. Regarding soil moisture observations, perhaps the main flash flood related applications to date have been – to a limited extent – for soil moisture data assimilation in distributed flood forecasting models (see Chap. 12), and for estimating flood inundation extents in post-event analyses of flooding events (see Chap. 7).

3.3.3 Snow

In some regions, the extent, depth and density of snow cover has an influence on flash floods, and measurements of wind speed, radiation and air temperature are sometimes required as inputs to snowmelt forecasting models. In flood forecasting models, as for the soil moisture component, a mass or volumetric accounting procedure is often used with occasional updates based on observations (see Chap. 5). However, in some cases, satellite and ground-based observations are used directly, particularly in water resources applications.

In countries which experience significant snowfall every year, in addition to the flood risk from spring snowmelt, the key drivers for monitoring typically include the avalanche risk, reservoir operations and/or the skiing industry. Both manual and automated recording techniques are widely used (e.g. World Meteorological Organisation 1992, 2009; Egli et al. 2009; Rasmussen et al. 2010). With a manual approach, observations are typically made at fixed locations on a regular basis (e.g. daily) and at less regular intervals (e.g. weekly) along snow courses through wooded and open areas. Some typical observation techniques include the use of graduated scales, rods or rulers, snow stakes, and daily clearance of a snow monitoring platform or board set aside for the purpose.

However, the use of automated approaches is increasing, although is still comparatively rare, and was reported by less than 10% of the national meteorological and hydrological services that responded to a 2008/09 survey (Nitu and Wong 2010). Also, occasional manual check observations are still required where sites are accessible. One of the earliest methods to be used was to add a heating element to recording raingauges to provide an indication of snow water equivalent (and to help to avoid gauges freezing up). However, gauges tend to under-record snowfall, and the measurement challenges are generally greater than for rainfall due to factors such as ice, drifting snow, and local topographic influences. For this reason, river level gauges are sometimes installed downstream of likely areas of snowmelt, but upstream of locations at risk, to provide additional backup and early warning in case of significant snowmelt events.

Some other automated techniques for monitoring snow water equivalent or density include gamma radiation attenuation sensors, radioisotype devices, and snow pillows. Gamma ray detectors are typically mounted at ground level and measure the absorption of natural background radiation by the water content, providing a snow water equivalent value. Radioisotype sensors operate on a similar principle although are less widely used due to the precautions needed with handling radioactive materials.

By contrast, snow pillows are mounted at ground level so that snow collects on top of the device, and consist of a flexible rubberized or metal container which contains an anti-freeze solution. The pressure changes are measured which result from the deformation of the container under snow loading, again giving an indication of the snow water equivalent. However, due to the cost and potential environmental risks, one simpler alternative which has been developed uses solid-state load-cell sensors which consist of large instrumented flat plates whose deformation depends on the depth of snow (Johnson et al. 2007).

Another technique - which only records snow depth - is to use a downward-looking ultrasonic sensor mounted on a mast or frame at heights of up to a few metres (e.g. Fig. 3.6). For example, this type of device is included in perhaps one of the most extensive networks of ground-based sensors worldwide; namely the SNOTEL network operated by the U.S. Department of Agriculture in the western USA (Schaefer and Paetzold 2000). Monitoring sites are installed at more than 700 locations, and typically include snow pillows and ultrasonic sensors, and often an automatic weather station. The resulting observations are typically recorded at 15 minute intervals and transmitted hourly using meteor burst telemetry.

In addition to these point observation techniques, a number of remote sensing options are available. For example, ground penetrating radars can be flown by helicopter or aircraft, pulled by snowmobile, or mounted on an array of fixed antennas to form a transect over a distance of several kilometres, and provide estimates for snow depth, density and water equivalent values (Lundberg et al. 2008). Low-cost vertically-pointing Doppler radars are also used in California to assist with forecasting of snow levels for input to rainfall-runoff flood forecasting models (White et al. 2012; see Box 12.1).

Satellite observations are also increasingly used to monitor the extent of snow cover and other parameters such as albedo (e.g. König et al. 2001; Shunlin 2008;

Fig. 3.6 Snow depth sensor (Met Office 2010; Contains public sector information licensed under the Open Government Licence v1.0)

Armstrong and Brun 2008). The most widely used application is probably for maps of snow cover, which have been available since the 1960s using visible imagery and more recently using passive microwave sensors. Much research has also been performed into monitoring snow depth and snow water equivalent using synthetic aperture radar, scatterometer and other approaches, with some operational products available at daily or longer timescales. For example, as part of a national flow forecasting system in Finland (Vehviläinen et al. 2005), both ground-based and satellite-based snow observations are used as part of routine model operations.

3.4 Observation Networks

3.4.1 Telemetry Systems

In the early days of hydrometry, observations were typically made once per day at raingauges and 2–3 times per day for river levels. Values were recorded manually by volunteers or paid observers and relayed by telephone, radio or telegraph if there was a requirement for near real-time data.

However, the ability to remotely monitor rainfall and river conditions has transformed the ability to provide flash flood warnings. Information now arrives soon after the time of observation in an electronic format suitable for display on maps and graphs and for input to flood forecasting and decision-support systems. As noted earlier though, observers still have a valuable role to play and the use of automated equipment does not remove the need for regular visits to instruments for maintenance and calibration checks.

In many countries, the use of telemetry systems for flash flood applications has only become widespread since the 1970s or 1980s. Initially the main constraints were cost and reliability and – to a lesser extent – the computer processing power needed to manage the incoming data; however these are much less of a factor nowadays. For example, in the USA, a major step forwards was the introduction in the 1970s of a standard protocol – the Automated Local Evaluation in Real-Time (ALERT) protocol – for hydrological data transmission (e.g. NOAA/NWS 2010). This has subsequently been adopted by many equipment suppliers and software vendors and is used in some countries outside the USA. The functionality has since been expanded to allow two-way transmission of data and continuous reporting of information.

A number of international initiatives have also helped to promote the wider use of telemetry in hydrological applications. For example, in 1963, the World Meteorological Organisation introduced the World Weather Watch programme to facilitate the exchange of meteorological information for use in weather forecasting. Information is exchanged via the WMO Global Telecommunication System (GTS) and this has included the development of standards for transmission by a variety of methods, including landline and satellite based telemetry systems (http://www.wmo.int/). A tiered approach is used consisting of a main (or core) network which links to regional and national networks. For national meteorological services the GTS is a key approach for exchanging data and forecast products.

The use of satellite telemetry in hydrology also dates back to that period (e.g. Paulson and Shope 1984) and accelerated with the launch of the first geostationary satellites as part of the NOAA GOES and European Meteosat programmes. These include a data collection and distribution capability for use with ground-based environmental stations, such as river gauges. A number of commercially operated geostationary and low earth orbit communication satellites are now also available, and provide various combinations of visibility (by latitude and longitude), polling options, and latency (in relaying observations). Of course, the use of telephone and radio-based telemetry pre-dates all of these developments.

To equip a monitoring site with a telemetry link, typically this requires addition of a data logger (if there is none already), a modem, lightning protection and – in some cases – an antenna. The power supply required depends on the method used and options include solar power, batteries and/or mains power. Additional channels are usually included to monitor parameters such as the battery charge and kiosk temperature and, for satellite telemetry, a GPS receiver is normally required to provide precise time and location information for use in transmissions. This overall combination of data logging and transmission equipment is often called a Data Collection Platform (DCP), as illustrated in Box 3.1 for example.

Table 3.2 summarises the main options which are available for the telemetry of hydrometeorological data. In practice, the methods which are used depend on a number of factors, including initial and operating costs, the data transfer rates required, current systems, power requirements, site security, local practice, and the distances and terrain to be covered. The technical viability of the approach also needs to be assessed in terms of the network coverage, reliability, potential signal interference, line-of-sight, and other factors, as appropriate. Also, for additional resilience, dual-path

Table 3.2 Some possible telemetry techniques for hydrometeorological data

Method	Basis of technique
Cellular	Data transmission using GPRS or GSM technologies, in some cases with the option to send SMS text message alerts directly from gauges to cell phone subscribers. However, the facilities available and performance vary between countries, networks and locations
Landline	Transmission using the Public Switched Telephone Network (PSTN) or leased/common-carrier/dedicated lines
Meteor burst	Reflection of radio signals from the ion trails left by microscopic meteors, and capable of transmission over distances of 1,000 km or more. Information is transmitted in bursts during suitable conditions
Radio	Direct (line-of-sight) VHF or UHF transmissions, with repeater stations as required. Repeaters are sometimes included alongside instruments, such as automatic weather stations.
Satellite	Transmission using meteorological, communications or other geostationary, polar or low earth orbit (LEO) satellites, including both national and private sector operators, in some cases with constellations of 50 or more low earth orbit satellites

approaches are increasingly used, particularly for critical gauges, and this option is increasingly offered by equipment suppliers. In some countries another option is to transmit data via existing emergency response networks.

For example, in the USA, radio-based telemetry is used for many local flood warning systems (see Box 6.1) whilst satellite-based telemetry is widely used for the national U.S. Geological Survey river gauging network (see Box 3.1). As discussed earlier, meteor burst techniques are used by the US Department of Agriculture for telemetry from snow-monitoring sites (see Sect. 3.3). In the UK by contrast, the main flood warning authorities use land-line based (PSTN) telephone telemetry almost exclusively for river and raingauge monitoring sites. In some cases, a combined or hybrid approach is used; for example with local communications to a hub by radio, leased line, satellite or cellular approaches and final transmission between regional centres by satellite or a wide area network (e.g. Fig. 3.7).

More generally, the issues of ownership, licences and routine and emergency maintenance of the network are factors to consider. For example, meteor burst and radio telemetry systems normally require the eventual operator to fund the initial costs of setting up the network, including repeater stations in some radio networks. However, once the system is operational, there are usually no charges for data transmission, although factors such as radio licences and repair, maintenance and upgrade costs obviously need to be considered. Internet, satellite, cellphone and landline based systems differ in that they make use of existing transmission networks. However these are often not designed specifically for emergency communications and may fail when they are most needed. In addition, connection charges are sometimes incurred, either as a fixed charge or related to data volumes, although some providers may provide low cost or cost free transmission options for flood warning and other public safety applications. Also, for landlines, additional cabling and signal amplifiers may be required if the

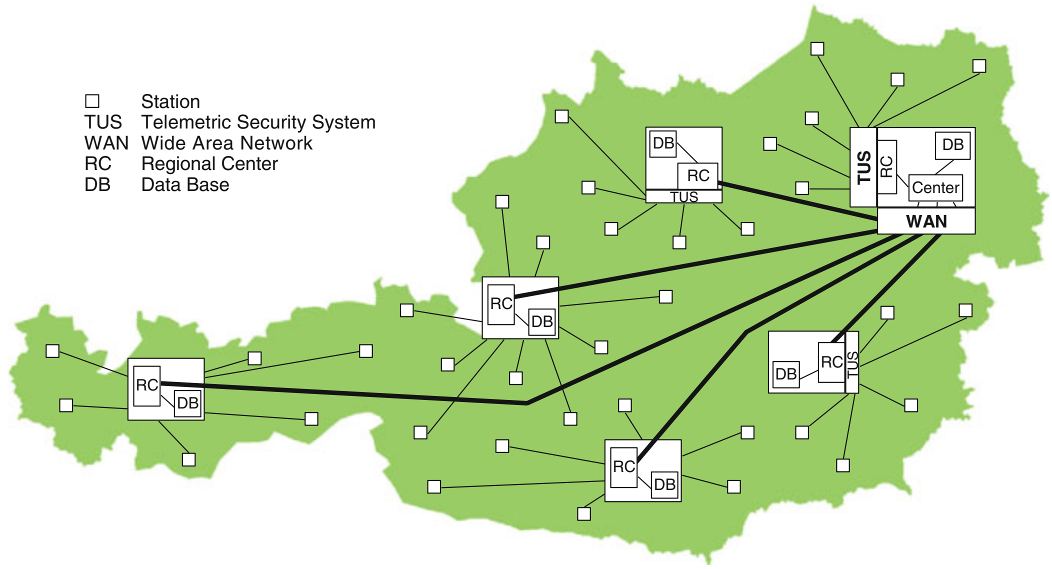

Fig. 3.7 Illustration of the data flow in the Automatic Weather Station network in Austria (Central Institute for Meteorology and Geodynamics, ZAMG; Rudel 2008)

site is not close to an existing line. In all cases a base station is normally required at the flood operations centre with equipment specific to the method(s) used, such as a radio mast or satellite dish and related software and computer equipment.

Another consideration is whether to use two-way (duplex) or one-way (simplex) systems. Duplex systems have the advantage that they allow the operator to request (or poll) data from an instrument, perform diagnostic checks, update software and check key parameters, such as battery power. By contrast, simplex systems – such as those used in some satellite and radio-based systems – usually only transmit at pre-defined time intervals and/or on exceedance of a critical rainfall or river level threshold; however systems of this type still require regular checks that the equipment is still functioning, or a daily test transmission.

For flash flood applications (and flooding in general), the likely performance in heavy rainfall and flood conditions also needs to be considered. For example with some shared networks there is a risk that the system will be overloaded during emergencies and/or affected by flooding at telecommunications hubs. Some possible ways of mitigating these risks include using multiple transmission routes and having fall-back arrangements in place at critical sites, such as observers with hand-held radios. A back-up or alternate control centre is another widely used option, with the transfer of operations being rehearsed as part of flood emergency planning exercises (see Chaps. 6 and 7).

Another factor to consider for flash flooding warning systems is the frequency of transmissions. In water resources applications, intervals of a few times a day, or even daily, are widely used but this is clearly too infrequent to resolve the details of a flash flood event developing over a period of minutes to a few hours. Accordingly, intervals of 1-, 5- or 15 min are widely used; however, to reduce transmission costs and/or power requirements, in some cases the stored values are transmitted at less frequent intervals when there is no significant flood risk, with clearly-defined procedures for switching to more frequent polling if there is any possibility of flooding. Alternatively event-based transmissions are used in some applications.

3.4.2 Information Systems

Most telemetry systems are operated using specialist computer software to control the receipt and polling of data. Systems of this type typically include a range of options for monitoring the status of individual instruments and the overall system. A map-based interface is usually included to show instrument locations and real-time readings. Some systems also include email, text message and other alarm-handling options for raising alerts when key thresholds are crossed, and the facility to remotely test and reconfigure equipment and to control devices such as video cameras and warning sirens.

For flash flood applications, due to the short time available, automated data validation and checking routines are particularly important. In some cases initial checks are performed by the data logger software at each instrument although more usually this is performed at the base station. The aim should be to at least identify or remove gross errors – without unintentionally excluding genuine extremes – before information is used in flood warning decisions and as an input to flood forecasting systems. Some systems are also programmable, allowing users to define more complex rate of rise, multi-criteria and other threshold criteria (see Chap. 8). Often two or more databases are operated in parallel; an operational ('rolling-barrel') store with raw unchecked data from the past few days or weeks and a main database for quality controlled datasets. For example, World Meteorological Organisation (2011) suggests that the following items are relevant to a flood forecasting and warning system: retention of raw data files, metadata identifying the origins of a dataset, documentation on major changes to datasets (e.g. changes in datums) and to individual values, and a catalogue of edits made, reasons for the changes and methods used.

There are many different systems and configuration options available commercially, in addition to those developed in-house by meteorological and hydrological services. For example, sometimes the telemetry aspects are included as part of an overall data management system which provides data archiving and retrieval facilities and a range of data validation, infilling and analysis options. Table 3.3 summarises some typical functionality for this type of system. In other cases, these components are included as modules within a flood forecasting system, and Chap. 5 describes the additional functionality which this typically provides. Alternatively, in some organisations the telemetry, data management and forecasting system components are kept completely separate; for example, if sourced from different suppliers or for operational reasons. As another alternative, some suppliers now offer partially or completed managed data collection, management and publication services, including

Table 3.3 Some typical options in a hydrological data management and telemetry system

Option	Description
Interfaces	
Data acquisition	Automated loading of data from a wide range of sources and transmission routes, including options to facilitate loading of manually reported observations received via web-based data entry forms, telephone, text message, fax or email
Data distribution	Automated transfer of time-series, grid-based and other data to decision support, flood forecasting and other systems, perhaps with a developer's toolkit to allow software to be developed for automated access from a user's own systems
SCADA	Links to specialized Supervisory Control and Data Acquisition (SCADA) systems at hydropower plants and other sites
Data processing	
Data quality indicators	The option to add comments and data quality flags or codes to individual values, and to maintain multiple copies of individual time series (e.g. raw, checked, interpolated)
Data validation	Graphical and automated options for quality control of incoming data, using range, threshold, persistence, rate of change and other criteria, such as comparisons with other data streams
Editing	Interactive editors for reviewing and changing data values and adding data quality control flags and comments, typically with password controlled access at a range of levels (view, edit, administrator etc.)
Infilling	Automated and/or interactive tools for infilling data at a single site (e.g. linear interpolation, constant value)
Metadata	Summaries of the information stored on the system following national or international metadata standards for sites, data types, geospatial standards etc.
Web services	Presentation of both raw and checked data on web sites as graphs, maps and tables, often with the underlying datasets available for download in XML, netCDF, ASCII, kml or other formats
Data analysis	
General	A range of analysis options; for example, for base flow index, double mass, flow duration, flood frequency, catchment rainfall, and other possibilities
Multi-site analyses	Tools for infilling and extending records based on data recorded at other sites (e.g. by regression, rainfall-runoff modeling, double mass analyses)
Rating curves	Tools for displaying, developing and applying stage-discharge and level-storage curves and for analyses of associated spot gauging and other data
Report generation	Generation of summary 'year-book' and other report formats for sub-daily, daily, monthly and annual values including mean, maximum, minimum values and other statistical outputs, with the option to customize the formats used
Flood warning	
Thresholds	Definition of single-value thresholds and possibly other types, such as rate or rise or multi-criteria thresholds (possibly using a suite of programming tools)
Alarm handling	Comparisons of real-time data with threshold values and raising alarms when values are exceeded, including maintaining an audit trail of system outputs and user entries
Dissemination	Automated transmission of alarms by email, text message and other options including publishing values to a website both publicly and with password controlled access, plus links to multi-media and other systems

password-protected access to a website displaying data from a user's monitoring network.

Typically the decision on which approach to use depends on cost, existing (legacy) systems, useability, vendor support, system security, connectivity with other systems, and other factors such as organizational policy. For flash flood warning systems, the resilience of the approach used is another key consideration: for example, separate telemetry, forecasting and warning dissemination systems are sometimes more robust to the failure of any one component, but more complex to manage (which introduces other potential risks). As noted earlier, a duplicate system is often maintained at a different site in case of complete failure at the primary site, with backup power and communication facilities at each location.

Another factor to consider is that, in some cases, meteorological and flood warning services use separate telemetry and information systems. Where real-time observations and forecasts need to be exchanged, this often requires the establishment of service level agreements and round-the-clock support during flood events, and sometimes the installation of dedicated telecommunications links. However, there are many standards and techniques available to facilitate sharing of data and forecast products, and these include:

- Data exchange formats – agreed formats for the exchange of information between organisations, of which the Extensible Markup Language (XML) is increasingly used. Another example is the BUFR format which is widely used for the exchange of meteorological data
- Data models – agreed storage formats for different types of data, often using relational database concepts. For example, many hydrological data management systems make use of commercially-available database systems, and the data model helps to define the structure of data storage tables and the relationships between them; for example, using SQL or bespoke software for data loading and retrieval
- Georeferencing – inclusion of sufficient information to identify the locations or spatial extent of all of the time series and other records stored on a system, including point locations (e.g. raingauges), line features (e.g. rivers), polygons (e.g. river basins) and other formats, following Open Geospatial Consortium (OGC) and other standards
- Metadata standards – international and other standards for the information used to identify and document datasets (and sometimes called 'data about data'). For example, for a hydrological monitoring station, this could include the name, number, location, date of opening, operator, parameters recorded, interval, units, maps, photographs and a number of other items

Most modern hydrological information systems include many of these features as standard as do many real-time flood forecasting systems (see Chap. 5). Much of this progress has been due to a range of national and international initiatives to standardize approaches, as illustrated by the examples in Table 3.4.

Table 3.4 Some examples of national and international initiatives relevant to hydrometeorological data management

Item	Location	Description
CUAHSI	USA	The Hydrologic Information System (HIS) component aims to develop data models, XML-based data interchange formats, metadata standards, software tools and web services to facilitate the analysis, visualization and modeling of hydrological data http://www.cuahsi.org/
INSPIRE	Europe	A European Commission initiative to establish an infrastructure for spatial information in Europe, including metadata and data exchange standards across a wide range of themes, including meteorological and natural hazards topics http://inspire.jrc.ec.europa.eu/
OpenMI	Europe	A standard interface to facilitate the exchange of information between databases, hydrological models and other modeling tools used in water-related and other environmental applications which has been adopted by a number of research and commercial organisations http://www.openmi.org/
WIS	International	A World Meteorological Organisation initiative for data management to provide improved data access, discovery, exchange and retrieval services, where possible making use of international metadata and interchange standards and building on the existing Global Telecommunication System http://www.wmo.int/

3.4.3 Gauge siting considerations

For flash flood warning applications, additional gauges may be required to support new flood warning schemes, flood forecasting model development, and a range of other applications. If a network is to be upgraded, then the design typically proceeds through a number of stages as illustrated in general terms by the example in Table 3.5. However, the steps required vary widely between organisations and countries and each situation requires its own solution.

For water resources applications, various guidelines are available for helping to decide on the optimum network configuration, depending on the climate, topography, elevation, accuracy requirements and other factors (e.g. Moss and Tasker 1991; World Meteorological Organisation 1994, 2009). However, less research has been performed on the design of networks for flood warning applications, although this topic is discussed in a number of reviews, including NOAA/NWS (2010), USACE (1996), Mishra and Coulibaly (2009), NOAA (2010) and World Meteorological Organisation (2009, 2011). Risk-based techniques are sometimes also used to provide guidance on the siting of instruments; for example in terms of the minimum raingauge network density, or the maximum distance for a river gauge upstream or downstream of a flood warning area, for a given level of flood risk (Andryszewski et al. 2005).

Table 3.5 Example of some typical stages in upgrading a flood warning observation network

Stage	Description
Feasibility study	Review of the current network (locations, condition, performance etc.), flood risk, operational requirements (e.g. warning lead times), flood forecasting requirements, catchment response times and characteristics, training needs, telemetry options, cost estimates etc.
Detailed design	Specification of the locations and types of instrumentation required, telemetry and information systems, training requirements, required forecast and other products, data dissemination routes, budget estimates, licences, site permissions, approvals etc.
Pilot installations	In some cases, initial trials to evaluate instruments, software and telemetry systems and organisational issues on one or more test catchments in a pre-operational setting
Implementation	Installation and commissioning of the system including civil works and factory and site acceptance tests and training of end users, and preparation of operation and maintenance procedures and manuals
Operations and maintenance	Long-term operation of the system, including preventative maintenance, repairs, upgrades and training, and ongoing system improvements

Theoretically-based approaches have also been developed for raingauge siting (e.g. Volkmann et al. 2010); for example, seeking to minimize the variance in estimates of mean areal rainfall or using cross correlations between gauges as a criterion for selecting gauge densities. As discussed in Chap. 5, for flood forecasting applications, another option is to assess the influence of network design options on model performance. For example, in addition to sensitivity tests using different combinations of gauges, some other factors to consider include the locations of communities at risk, the required forecasting points, catchment response times, typical flooding mechanisms, and the flood warning lead times required for an effective response. Analyses of rainfall and runoff distributions during previous flood events and of typical storm scales, paths and speeds also provide useful information; for example, using weather radar images and rainfall intensity estimates (see Chap. 2). If accurate (e.g. GPS-based) coordinates for gauges are available, this also allows the general setting to be viewed in three dimensions using digital terrain models; for example to assess the likely influences of topography.

However, with the exception of some purpose-made flood warning systems, in practice many observation networks tend to evolve in a more ad-hoc way to meet the needs of several applications. These typically include water resources monitoring, agriculture, reservoir operations, navigation and pollution control, as well as flood warning. Also, considerations of road access, power supply, landowner permissions, site security, telemetry options and the availability of local staff sometimes lead to instruments being installed in locations which would not be the first choice from a flood warning perspective. For example, the coverage of raingauges and automatic weather stations is often sparse at higher altitudes, particularly in the headwaters of

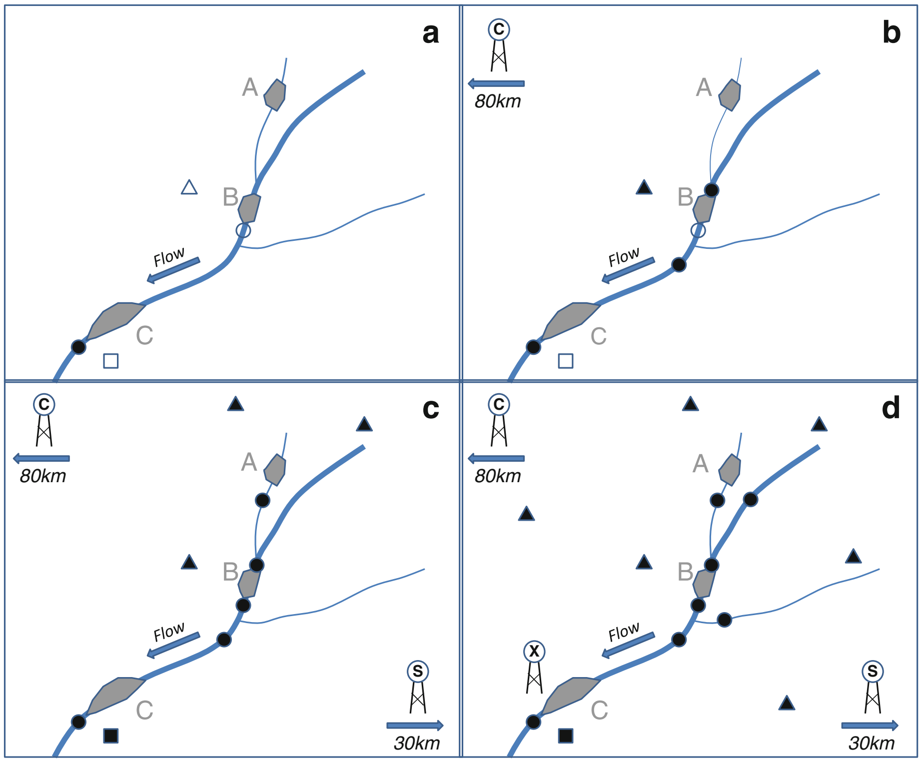

Fig. 3.8 Illustration of the development of a flood warning service for a hypothetical catchment. Period (**a**) basic warning service for city C using water resources gauges. Period (**b**) service extended to town B; flow routing forecasting model developed for city C; C-band radar installed as part of national network, flash flood guidance approach introduced for region. Period (**c**) community-based flood warning system established for village A; weather station now on telemetry; S-band radar installed. Period (**d**) more gauges installated to support operation of an integrated catchment model for all locations at risk; X-band radar installed to support surface water (pluvial) warning service for city C. *Triangles* = raingauges, *Circles* = river gauges, *Square* = weather station, Towers = X-, C- or S-band weather radars. *Open symbols* = manual observations, *Solid symbols* = telemetry sites

river catchments. Of course, if the opportunity and budget arises to design or upgrade a network from first principles then a more objective approach can be adopted.

Another consideration is that, in some countries, observation networks are operated by several organizations. However, if suitable data exchange protocols can be agreed, it may be possible to exchange data in real-time and pool resources when installing new equipment. For example, Fig. 3.8 provides a simple illustration of the development of a monitoring network over several decades. This situation, although hypothetical, is fairly typical for organisations with a long tradition of river monitoring, although of course the details vary widely between catchments and countries.

Typically, the rate of development for the flood warning component is linked to the level of flood risk, budgets, the high flow performance of existing gauges, organizational policy, national targets (if any) and – in some cases - political pressure for improvements. Other factors sometimes play a role, such as the pace of development of the national weather radar network (if any) and the requirements to support the operation of flood forecasting models. For example, in some cases additional raingauges are installed to fill in gaps in a weather radar network or for use in real-time adjustment of radar rainfall outputs (see Chap. 2). Other river gauges may be installed as backups at high risk locations in case of telemetry or gauge failures during a flood event, and temporary gauges installed in support of flood defence or reservoir construction schemes or to evaluate site security.

In some cases it is also possible to use the same sites for different applications; for example, raingauges are often installed (or co-located) alongside river gauges, and it is sometimes possible to upgrade water resources gauges to improve monitoring at high flows. However, in the latter case, it is worth noting that gauges are often installed without regard to high flow performance and affected by problems which cannot easily be solved; for example, due to bypassing by flows on the floodplain and backwater influences from confluences or structures. In this situation (and others), hydrological and hydraulic modeling studies can sometimes help to assess potential issues with instrument performance. Some examples include assessing the impacts of backwater effects and floodplain flows, deriving estimates for catchment and river response times for input to an analysis of likely flood warning lead times (see Chaps. 5 and 7), and estimating the minimum required elevations for electrical equipment to avoid the risk of damage from flooding.

In some cases, the potential options need to be considered as part of an overall cost benefit or multi-criteria analysis of the types discussed in Chap. 7, considering both purchase and operating costs and a range of other factors. For example World Meteorological Organisation (2011) recommends that procurement contracts for instrumentation cover the following elements: supply of instruments, compliance with international standards of manufacture and performance, installation and calibration, testing and commissioning of instruments and the network, and contracts for warranty, service, supply of spares and maintenance. More generally, the need for regular site visits, calibration checks and data quality control cannot be overemphasized, including the upkeep of equipment such as current meters and ADCP devices. This requires that suitable long-term funding is in place with associated staff resources, training programmes and career structures (e.g. NOAA 2010; World Meteorological Organisation 2009, 2011).

The intervals between major upgrades or replacement of equipment also need to be considered and – as discussed in Chap. 7 – the possible opportunities for cost-sharing with other potential users; for example for water resources or agricultural applications. In particular, if a network has multiple uses, this often helps both with obtaining funding and the long-term maintenance and sustainability of the system through widening the number of users and potential sources of funding. This also helps to maintain systems and staff skills if a region has a distinct flood season (or seasons), with key equipment little used at other times.

Another consideration is the risk of theft or vandalism, which is a problem that plagues many organisations. Some approaches which are used to reduce losses include "fences, plating, camouflage, enclosure within buildings" (Flood Control District of Maricopa County 1997). In some cases – depending on cost and reliability - small low-power (no solar panel), low-visual impact devices might reduce problems, such as non-contact radar or ultrasonic river gauges, and solid-state raingauges.

In some less-developed countries, there may also be advantages in choosing a site some way distant from the ideal location, such as a secure government compound (for raingauges) or a road bridge with police or other checkpoints (for river gauges). In rural areas, seeking help from local communities often provides some additional protection; for example, by providing more options for safe locations to install equipment and recruiting volunteer or paid observers. Where vandalism is already a problem, community-awareness raising exercises may also help, and making real-time data available locally so that users such as farmers, boat operators or anglers gain some direct benefit from the information. In the latter case, some possible dissemination routes include publishing observations on a website and direct communication of values using options such as text messages, email, and smartphone applications.

3.5 Summary

- River level and flow observations play a key role in many aspects of the flash flood warning process. This includes monitoring levels against flood warning thresholds and as an input to flood forecasting models. Soil moisture estimates are also widely used together with snow observations in some regions
- The main techniques used for river level monitoring include float-in-stilling-well, pressure transducer and bubbler gauges, and non-contact approaches such as downward-looking ultrasonic and radar devices. For flash flood applications, gauges need to be sited so that electrical equipment is above likely flood levels and the gauge range includes the maximum levels likely to be observed
- Discharge observations are typically made using Acoustic Doppler Current Profilers, although current meters are still widely used. The resulting spot gaugings are then used to develop stage-discharge relationships for use in converting river level observations to flows. There are many issues to consider with the development and maintenance of rating curves, including the uncertainties due to sedimentation, erosion, vegetation and backwater influences. For these reasons, purpose-made gauging structures and ultrasonic or electromagnetic flow recorders are occasionally used although cost is often a limiting factor
- Soil moisture measurement techniques include dielectric and heat dissipation probes, and satellite-based microwave observations. However, due to the wide spatial variations in values, soil moisture accounting techniques are perhaps more widely used than direct observations. Models of this type typically estimate soil moisture on a gridded basis from raingauge or weather radar observations and evapotranspiration estimates derived from weather station observations
- Snow observation techniques include snow pillows, downward-looking ultrasonic gauges, and load-cell sensors. Satellite observations are widely used for

monitoring snow cover, but less frequently for snow water equivalent estimates. However, manual observation techniques remain widely used at fixed observation points, along transects and from snowmobiles and aircraft

- Telemetry systems are widely used in flash flood warning and forecasting systems. The main options include UHF or VHF radio, and cellular (GSM, GPRS), satellite, meteor burst, and landline techniques. Sometimes more than one method is used at each gauge to provide additional resilience to network failures. For flash flood applications some particular issues to consider are the performance in heavy rainfall and flood conditions and – particularly for shared networks – the risks of network overloading or failure during emergency conditions
- Information systems play a key role in processing and archiving observations. Some typical functionality includes the option to monitor observations against pre-defined thresholds for use in issuing flash flood warnings, and a range of data validation, analysis and display tools. Increasingly systems use a map-based user interface and adopt internationally accepted data exchange, data storage and metadata standards
- Flash flood observation networks often tend to develop in an ad-hoc way, although design guidelines are available for some components. However, the development of techniques to optimise gauge densities and locations is an active area for research. Site-specific issues also need to be considered, such as the ease of access, telemetry coverage, and the risks from flooding or vandalism. In some cases, improvements need to be justified using a cost-benefit or multi-criteria approach and the investment linked to the level of flood risk

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Chapter 4
Rainfall Forecasting

Abstract Rainfall forecasts are widely used as part of the flash flood warning process and typically allow warnings to be issued earlier in an event than would be possible from observations alone. In recent years, the resolution of atmospheric models has improved significantly and in some cases now approaches the scales of interest for use with flood forecasting models. Nowcasting techniques are also widely used. This chapter provides a brief introduction to these techniques and to the climatology of flash floods. Some key operational considerations are also discussed including approaches to issuing heavy rainfall warnings, forecast verification techniques, and the typical forecast delivery mechanisms between meteorological and hydrological services.

Keywords Flash flood climatology • Nowcasting • Numerical Weather Prediction • Post-processing • Forecaster inputs • Heavy rainfall warnings • Forecast verification • Forecast delivery mechanisms

4.1 Introduction

Rainfall forecasts provide flood warning authorities with the potential to issue earlier warnings of the risk of flash floods than would be possible from river or rainfall observations alone. Longer-range forecasts are also increasingly used to help in deciding whether to take precautionary actions in case of flooding, such as scheduling staff rosters and checking and pre-positioning equipment. Although the terminology varies between countries, some ways in which rainfall forecasts are typically used include:

- Flash flood advisories – initial alerts based largely on a forecaster's experience and interpretation of model outputs regarding the types of conditions which typically lead to heavy rainfall in an area and - in some cases - flash flooding

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- Heavy rainfall warnings – warnings issued when forecasts show that pre-defined depth-duration thresholds, typical of flooding conditions, are likely to be exceeded; for example 50 mm in 6 h, or a 60% probability of exceeding 30 mm in 2 h
- Flash flood guidance techniques – rainfall threshold approaches which take account of current catchment conditions; for example, by estimating the additional rainfall required to cause flooding, based on current soil moisture conditions
- Flood forecasting models – models which use rainfall forecasts directly to provide general or site-specific flash flood forecasts; for example, using 20-member ensemble rainfall forecasts provided at hourly intervals for the next 24 h at a grid scale of 1 km

Rainfall thresholds are widely used in the warning process for debris flows and surface water flooding in urban areas (see Chaps. 9 and 10) whilst flash flood guidance techniques and flood forecasting models are often used in river applications (see Chap. 8). Generally, for a given lead time, the amount of detail provided in terms of the timing, location, magnitude and duration of flooding increases with each of these approaches, with a corresponding decrease in uncertainty.

For weather forecasting, the two main modelling approaches which are used are:

- Nowcasting – a long-established technique in which the current motion of rainfall, clouds, fog and other meteorological features is extrapolated into the future based on current and recent weather radar or satellite observations, in some cases guided by the outputs from models and observations from other sources (e.g. lightning detection systems)
- Numerical Weather Prediction (NWP) – Physically-based models which solve approximations to the mass, momentum and energy conservation equations for the atmosphere, taking account of water, momentum and heat transfer at the land-surface and, in many cases, the ocean surface. Typically local or regional scale models are embedded within a coarser-scale global model and are initialized using a process called data assimilation which combines observations from many sources

These types of models are typically operated by national meteorological services although some research centres and private sector forecast providers also have an operational forecasting capability. Nowcasts are normally used for short lead times and Numerical Weather Prediction model outputs at longer lead times. For example, the World Meteorological Organisation (2010a) provides the following definitions for these timescales: nowcasting (current weather parameters, and 0–2 h), very short-range (up to 12 h), short-range (12–72 h), medium-range (72–240 h), extended-range (10–30 days), long-range (30 days to 2 years). In practice, nowcasts are typically considered to provide useful outputs for lead times of up to about 6 h ahead and NWP outputs from hours to days ahead.

Figure 4.1 illustrates how these two types of output are typically made available to end users such as a flood warning service. Each product is issued at fixed intervals based on a cycle of data assimilation (or analyses, in the case of nowcasts), model runs and post-processing. In this hypothetical example, NWP outputs are available

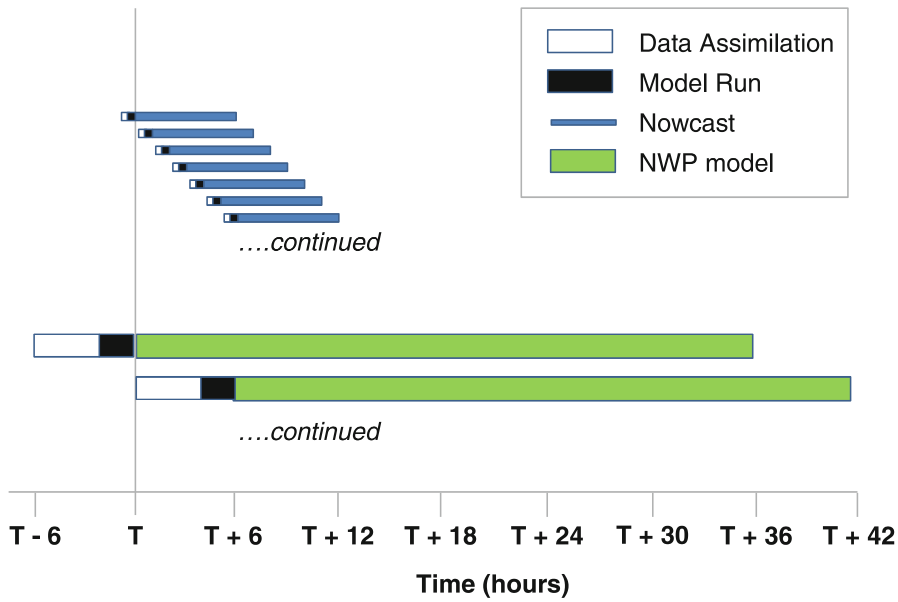

Fig. 4.1 Illustration of a forecasting and data assimilation cycle spanning two Numerical Weather Prediction (*NWP*) model runs. See text for description

every 6 h for a forecast lead time of 0–36 h and nowcast outputs every hour for a lead time of 6 h. For convenience the time required for post-processing is omitted from the figure.

However, nowcasts are usually available at more frequent intervals than this and are typically provided at sub-hourly (e.g. 15 minute) intervals when based on weather radar observations. The spatial resolution is constrained by that of the underlying observation system and is typically 1–5 km for weather radar- and 5–15 km for satellite-based estimates (see Chap. 2). Although forecasts are often issued for up to 6–8 h ahead, the operationally useful lead times are sometimes much less than this for some types of events, such as thunderstorms, and in some cases no more than 1–2 h.

The use of Numerical Weather Prediction model outputs in flash flood applications is a more recent development. In the past this was due mainly to the relatively coarse resolution compared to the hydrological scales of interest. For example, during the 1990s, the typical grid length for a regional-scale model was in the range 10–25 km, typically providing forecasts for up to 36–120 h ahead updated every 6–12 h. Also, in practice, the spatial scales or wave lengths which can be resolved without attenuation are typically 3–5 times the grid length, placing some limitations on the scale of atmospheric features which can be resolved (e.g. Lean and Clark 2003; Persson 2011).

However, in recent years, several meteorological services have started to use non-hydrostatic mesoscale models operationally. The horizontal resolutions are now typically 4 km or less and in some cases updates are available every hour for 12–24 h or more ahead. Here the term mesoscale is defined as 'pertaining to atmospheric phenomena having horizontal scales ranging from a few to several hundred

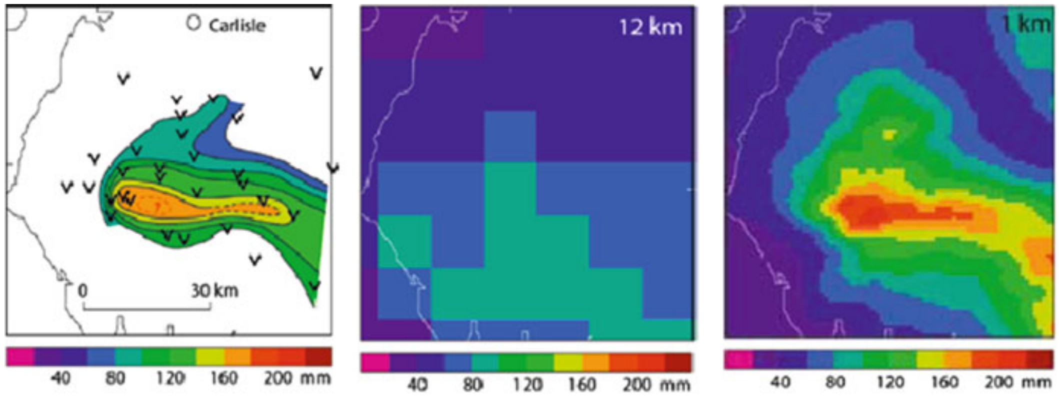

Fig. 4.2 Comparison of observed values and hindcasts at a 12 and 1 km resolution using the Met Office Unified Model for a major rainfall event in northwest England in January 2005 which resulted in flooding to almost 2,000 properties in the city of Carlisle (Cabinet Office 2008, © Crown Copyright 2008)

kilometers, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones, and topographically generated weather systems such as mountain waves and sea and land breezes' (AMS 2012). However, the term convective-scale is typically used when model grid lengths are of the order 1–2 km.

This approach often provides significant improvements in the accuracy of rainfall forecasts (e.g. Fig. 4.2). Post-processing techniques are also increasingly used to downscale outputs to locations of interest and include statistical, weather matching (analogue) and dynamic approaches. Also, since the 1990s the use of ensemble forecasts has become standard practice in many meteorological services and the outputs are increasingly used in flood forecasting applications. Probabilistic nowcasting products are another recent development, with the first operational implementations starting in the period 2005–2010 (approximately).

This chapter provides an introduction to these techniques, after first discussing some of the meteorological causes of flash floods. Some key operational considerations are also discussed, including approaches for issuing heavy rainfall warnings, forecast verification techniques, and mechanisms for transferring forecast products between meteorological and hydrological services. Descriptions of the underlying theory are available in the many texts on meteorological forecasting, including World Meteorological Organisation (2000), Kalnay (2002), Stensrud (2007) and Markowski and Richardson (2010).

Chapter 12 also briefly discusses several recent research developments in rainfall forecasting techniques which are potentially relevant to flash flood applications. These include the development of seamless or blended forecasts and of improved decision support systems for extreme events. Here, a seamless forecast is one which aims to provide spatially consistent probabilistic estimates from the present (i.e. including observations) through to long-range seasonal forecasts; an aim which once achieved could potentially combine multi-sensor precipitation estimates (see Chap. 2), nowcasts, and global, regional and local model outputs into a consistent suite of products. Several meteorological services are already well advanced in this area; for example in working towards operational products which combine nowcasts and short-range model outputs into a single ensemble product.

4.2 Flash Flood Climatology

One of the challenges in flash flood forecasting is to identify the conditions – or combination of conditions - likely to result in a risk to people, property and infrastructure. An understanding of the precursors to heavy rainfall is therefore a key requirement for both meteorological and flood forecasting applications. In particular, this can help to provide an indication of locations potentially at risk and the maximum forecast lead times which are likely to be possible. For example, the life cycle of a thunderstorm is sometimes less than an hour, whilst intense rainfall can persist for a day or more during the monsoon season and with slow-moving tropical cyclones. Generally, larger scale atmospheric features are predictable over longer timescales than smaller scale convective events (e.g. Fig. 4.3). However convective storms can be associated with larger scale features causing localized periods of intense rainfall which are more difficult to anticipate.

There have been many studies of the causes of flash flooding and the findings vary widely between regions and countries. For example, in arid zones one of the classical

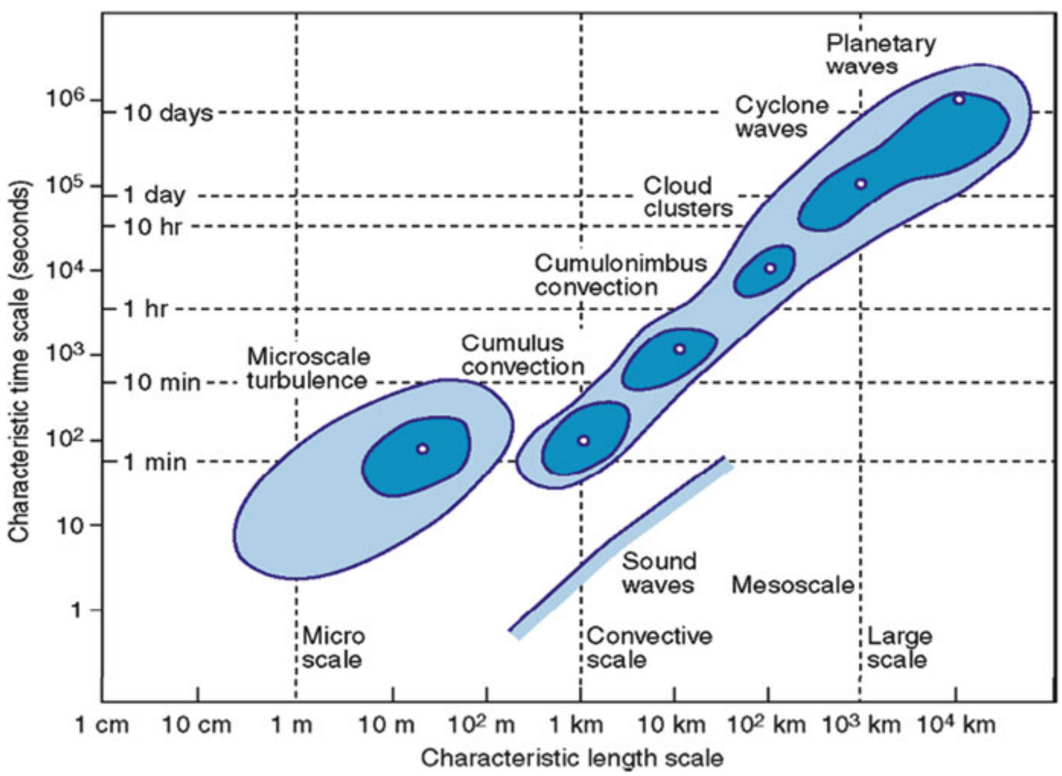

Fig. 4.3 A schematic illustration of the relationship between atmospheric scale and timescale. The typical predictability is currently approximately twice the timescale, but might ultimately be three times the timescale (Persson 2011; Source ECMWF)

Table 4.1 Some examples of meteorological factors leading to flash floods

Location	Description
Central and Southern Europe	Based on studies for flash-flood prone regions in seven countries, some common causes of flash floods appeared to be intense autumn convective storm events over large areas (sometimes 1,000 km^2 or more) in the Mediterranean area. By contrast, in Central European countries (Austria, Slovakia and Romania) these extremes tend to occur in the summer months and often on smaller catchments (<500 km^2) indicating a different climatic forcing. The flash flood regime in Northern Italy was found to be intermediate between these two cases (Gaume et al. 2009)
UK	In a study of 50 extreme rainfall events in the UK in the twentieth century, 30 were identified as predominately convective (e.g. thunderstorms), 15 as frontal and 5 orographic. The highest number of events was in the summer months of June–September. All of the orographic events "occurred in winter in moist west to southwest airflows, and 80% of the frontal cases involved a slow-moving depression to the south or east and also a slow moving frontal system". (Hand et al. 2004)
USA/Southern Europe	A study of flash flood events in the continental USA and Mediterranean Europe considered the meteorological parameters indicative of prolonged, intense rainfall for the following types of climatic regions: tropical; mountainous, mid-latitude, humid; mountainous dry climate; U.S. Great Plains. Some relevant parameters – depending on the region - included the strength of the low-level flow, stationary or slow moving storms (e.g. tropical cyclones), low-level dewpoint temperatures, surface precipitable water, a deep above freezing cloud layer, meteorological boundaries (e.g. a pre-existing cold front or rain-cooled relatively dense air from earlier thunderstorms) and orographic influences (e.g. regeneration, enhanced low-level lift) (Kelsch 2001)
USA	The main meteorological causes of flash floods in the USA were identified as "intense rainfall from slow-moving thunderstorms, thunderstorms that repeatedly move over the same location, or excessive rainfall from hurricanes or other tropical systems. Along the West Coast of the United States, in contrast, flash floods frequently are caused by orographic precipitation—that is, precipitation influenced by mountainous terrain. There, flash floods are typically associated with land-falling extratropical cyclones and fronts during the winter months, rather than summer thunderstorms" (National Academy of Sciences 2005). For example, an analysis for the period from 1996 to 2005 (Ashley and Ashley 2008) suggested that "mesoscale convective systems were responsible for 36% of the total number of flood fatalities over the period" and "deadly flash floods are found throughout the United States and are associated with five types of dominant surface features, with those generated by frontal lifting the dominant type"

runoff generation mechanisms is for a thunderstorm in distant hills to cause a flash flood to appear further downstream in a previously dry river bed. In the tropics, by contrast, flash floods are often caused by tropical cyclones, and are followed by more widespread flooding of lowland (plains) rivers a few hours or days later. Local orographic influences from hills and mountains can also have a major effect on the timing, location and magnitude of rainfall, in part depending on the wind direction relative to steeper ground.

Despite these difficulties, it is often possible to distinguish local or regional indicators of the potential for flash floods and Table 4.1 summarises some findings from

Table 4.2 Some meteorological causes of flash floods and related events. Definitions are from NOAA/NWS (2012) unless otherwise stated

Type	Typical definitions	Examples of flash flood events
Atmospheric river	… narrow corridors of water vapour transport in the lower atmosphere several hundred kilometres wide and extending for thousands of kilometres, sometimes across entire ocean basins (Ralph and Dettinger 2011).	See Box 4.1
Cut-off low	A closed upper-level low which has become completely displaced (cut off) from *the* basic westerly current, and moves independently of that current. Cutoff lows may remain nearly stationary for days, or on occasion may move westward opposite to the prevailing flow aloft (i.e. retrogression)	Extensive rainfall and riverine and flash flooding over a period of three days in KwaZulu Natal, South Africa in March 2003 (Singleton and Reason 2007)
Front	A boundary or transition zone between two air masses of different density, and thus (usually) of different temperature. A moving front is named according to the advancing air mass e.g. cold front if colder air is advancing	Extensive urban-drainage related flooding in the city of Hull, England, 2007 (Coulthard et al. 2007; see Chap. 10)
Mesoscale convective system	A complex of thunderstorms which becomes organized on a scale larger than the individual thunderstorms, and normally persists for several hours or more. MCSs may be round or linear in shape, and include systems such as tropical cyclones, squall lines, and MCCs (among others). MCS often is used to describe a cluster of thunderstorms that does not satisfy the size, shape, or duration criteria of an MCC (*MCC = Mesoscale Convective Complex*)	Heavy rainfall in Gard province in 2002 led to one of the most severe flood events on record in southern France (Anquetin et al. 2009; see Chap. 8)
Monsoon	A thermally driven wind arising from differential heating between a land mass and the adjacent ocean that reverses its direction seasonally	Severe surface water flooding in Mumbai, India, 2005 (Gupta 2007; see Chap. 10)
Thunderstorm	A local storm produced by a cumulonimbus cloud and accompanied by lightning and thunder	A major flood in the Big Thompson canyon, USA, 1976 (Gruntfest 1996; see Chap. 8)
Tropical cyclone	A warm-core, non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters with organized deep convection and a closed surface wind circulation about a well-defined center	Debris flows and flash floods arising from Tropical Cyclone Morakot, Taiwan (Chien and Kuo 2011; see Chap. 9)

research studies and reviews in Europe and the USA. Internationally, some meteorological causes cited in the literature include Atmospheric Rivers, cut-off lows, frontal systems, Mesoscale Convective Systems, monsoons, thunderstorms and tropical cyclones. These terms are defined in Table 4.2 and Chapters 8 to 11 provide further examples. More generally, the National Academy of Sciences (2005) suggests that some key ingredients of flash-flood producing storms (in the USA, at least) are:

- *an* ample and persistent supply of water vapor
- a mechanism to facilitate uplift of air in which the moisture condenses and precipitation forms
- a focusing mechanism (or combination of focusing mechanisms) that causes precipitation to occur continuously or repeatedly over the same area

So, whilst there are no generally applicable rules or guidelines on the criteria for anticipating flash flood generating storms, forecasters in a region (both meteorological and hydrological) tend to develop an understanding of typical risk factors. In some organisations, these findings are encapsulated into heuristic rules and decision support tools and this topic is discussed further in Sect. 4.4.

Box 4.1 Atmospheric Rivers

Atmospheric rivers are narrow corridors of water vapour in the lower atmosphere several hundred kilometres wide and sometimes extending for thousands of kilometres across the oceans (Ralph and Dettinger 2011). Typically they result from fast-moving low-level jets along the zones just ahead of the cold front in warm sectors of major winter cyclones (e.g. Neiman et al. 2008; Stohl et al. 2008; Dettinger et al. 2012).

The meteorological understanding of these processes has been greatly assisted by observations as part of a series of experimental field campaigns in California (see Box 12.1). In particular it has been shown that in California and the Pacific Northwest heavy orographic precipitation and flooding is often associated with land-falling events of this type. Subsequent studies have shown that atmospheric rivers can also occur in other mid-latitude coastal regions such as the southwest Norwegian coastline (Stohl et al. 2008), western South America (Viale and Nuñez 2011) and in parts of the eastern USA (Moore et al. 2012).

Figure 4.4 shows an example of a land-falling atmospheric river based on SSM/I microwave imagery from a polar orbiting satellite. This event resulted in more than 200 mm of rainfall along several hundred kilometres of the Californian coast in the period 13–14 October 2009, with more than 410 mm observed at one site (Ralph and Dettinger 2011). As with a number of other extreme precipitation events of this type there was a strong connection to a

(continued)

Box 4.1 (continued)

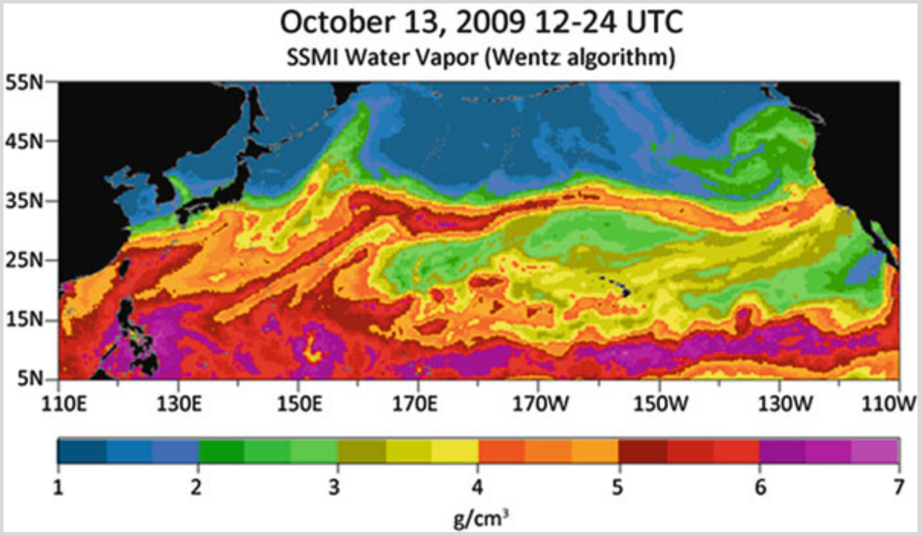

Fig. 4.4 Example of a land falling atmospheric river on 13 October 2009 showing the 12-h vertically integrated water vapour from 1200 to 2400 UTC derived from SSM/I microwave imagery (NOAA/Earth System Research Laboratory; http://www.esrl.noaa.gov/psd/atmrivers/)

tropical water vapour reservoir, which in this case was in the Western Pacific. This is a condition sometimes referred to as a "tropical tap".

Forecasting the extent and depth of rainfall can be particularly challenging when an atmospheric river passes over complex mountain terrain. For example, Fig. 4.5 shows a conceptual representation of an event which occurred when a moist low-level airstream originating in the Pacific Ocean passed over the western part of the Santa Cruz mountains which lie to the north of the coastal city of Santa Cruz in California (Ralph et al. 2003). This led to heavy precipitation on windward slopes although rainfall was lower in the rain-shadow area of the Santa Lucia mountains which lie a short way to the south.

The figure also shows estimates for the dividing streamline between the rainshadow area and the more intense rainfall to the west. During the event, Pescadero Creek to the west of this streamline experienced its flood of record whilst the San Lorenzo River to the east experienced less severe rainfall, resulting in only the fourth highest flood. This highlights the crucial role of wind direction in determining specifically which watersheds will experience the heaviest rainfall - and potentially flooding - during a landfalling atmospheric river event.

The observations were made during an intensive meteorological observation campaign and were remarkable in that they also included research aircraft observations of atmospheric river conditions offshore. This enabled flash

(continued)

Box 4.1 (continued)

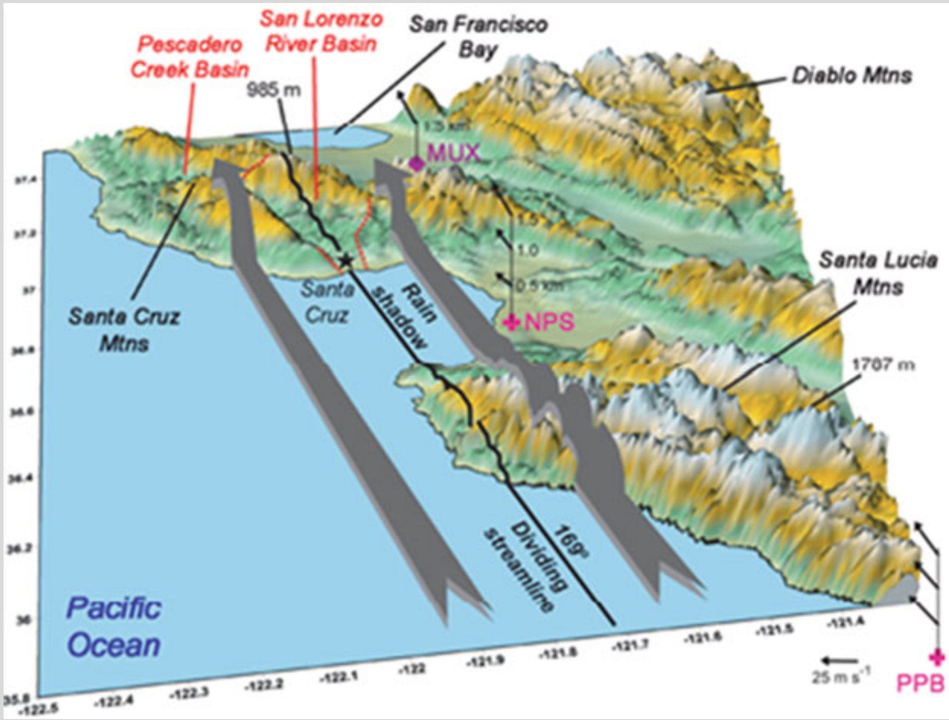

Fig. 4.5 Conditions during a key 4–6 h period associated with a landfalling atmospheric river that caused major flooding in 1998 along the Central California coast. The ribbons represent the averaged airflow in the period from 2200 UTC on 2 Feb to 0400 UTC on 3 Feb 1998. The locations of an S-band (NEXRAD) weather surveillance radar (MUX) and two wind profilers (NPS, PPB) are also shown (Ralph et al. 2003)

flood warnings to be issued hours in advance of the record flooding which subsequently occurred, and allowed the pre-positioning of local emergency responders, who rescued more than 100 people (Morss and Ralph 2007).

4.3 Forecasting Techniques

4.3.1 Nowcasting

4.3.1.1 Basis of Technique

Nowcasting was one of the first meteorological forecasting techniques and is used for rainfall, fog, snow showers, and other meteorological features. Alternative names include extrapolation forecasts and - for rainfall - very short term quantitative precipitation forecasts.

The basis of the method is to extrapolate the direction and evolution of a feature, based on observations of its location, extent, rate of growth or decay and/or intensity. Calculations of this type are nowadays performed mainly by computer, with models used to automatically identify key features and estimate their future trajectory. Numerical Weather Prediction model outputs are increasingly used as part of this process so that nowcasting is sometimes regarded as a form of post-processing of outputs. However, the nowcasting component has the advantage of running many times faster, allowing more frequent outputs at a higher resolution. The application to fast-developing events such as thunderstorms is therefore an active research area.

For rainfall forecasting, the maximum lead times for which nowcasts show skill depend on a number of factors. These include the type of storm, topographic influences, the quality and resolution of the underlying observations, and the algorithms used. The practical limit is often stated to be 6 h although as indicated earlier can be considerably less for convective events. Where Numerical Weather Prediction model outputs are used, nowcast products typically use a greater weighting for that component at longer lead times, as the influence or ‘memory’ of initial conditions decays. In addition to the extrapolation process, some key distinguishing features between products include (e.g. Browning and Collier 1989; Golding 1998, 2000, 2009; Ebert et al. 2004; Wilson 2004; Wilson et al. 2010; World Meteorological Organisation 2010b):

- Model guidance – whether the wind fields and selected other outputs from Numerical Weather Prediction models are used to guide the nowcasting process
- Probabilistic content – whether the forecasts are deterministic or probabilistic and, in the latter case, the ensemble generation process used
- Supplementary observations – whether additional information is used to assist with identification of areas of rainfall and in the advection process; for example, lightning fix, wind profiler, Doppler wind, GPS humidity and satellite-based cloud and wind observations

Regarding the extrapolation or advection component, many different approaches have been developed both to identify and translate areas of rainfall. The main options include considering areas of rainfall in terms of objects, centroids or on a grid-by-grid basis. Values are then either translated unchanged or allowing for growth, splitting and dissipation. Some typical approaches include correlation, time series analysis, artificial intelligence and/or pattern-matching techniques. Scale decomposition approaches have also been developed for some applications (see later).

For example, Fig. 4.6 illustrates the difference between the simplest type of nowcasting systems, which simply extrapolate areas of rainfall, and more complex forms which make use of model outputs and allow for growth, splitting and decay. The example is for the idealized case of a storm approaching a town and shows the storm location at the current time (‘time now’) and the forecast values 1- and 2-h ahead. The more complex scheme forecasts an area of heavy rainfall likely to pass over the town which is not predicted by persistence alone.

As indicated earlier, many rainfall nowcasting products are designed for use with weather radar observations. However, satellite-based schemes are sometimes used to

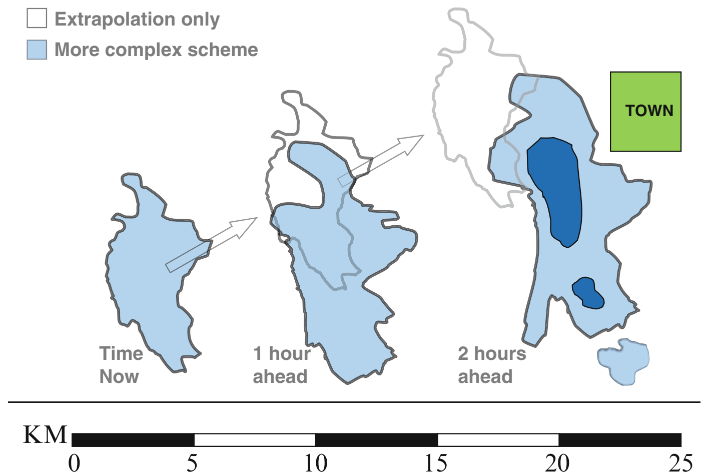

Fig. 4.6 Illustration of two approaches to nowcasting; extrapolation alone, or a scheme which allows for storm growth, splitting and decay (Adapted from Sene 2010)

infill gaps in the coverage or where there is no radar network available; for example in some regional Flash Flood Guidance systems (see Chap. 8). Typically these make use of consecutive infrared observations of cloud type, intensity and size from geostationary satellites although other approaches are available, combining observations from both geostationary and polar orbiting satellites to derive initial estimates for the precipitation field (see Chap. 2).

More generally, the latest nowcasting techniques typically use multiple observation systems and provide probabilistic outputs, as illustrated by the following two examples:

- NORA – an analogue-based technique developed by MeteoSwiss (Panziera et al. 2011) which is one of a number of nowcasting and other forecasting techniques used in the Swiss Alps. The main inputs are weather radar Doppler wind velocities at upper, mid and low levels and for cross barrier (Alp) flows and – to provide an indication of atmospheric stability - automatic weather station measurements of air temperature, pressure and humidity at two different elevations. A database is then searched to select the past conditions most similar to the current situation, from which a sample of events is chosen. A subset is then chosen based on statistical comparisons of the associated radar precipitation fields with current values. The radar rainfall sequences which followed those events are then used to form an ensemble rainfall forecast with outputs at 5 minute intervals for up to 8 hours ahead
- STEPS – a probabilistic nowcasting technique which was jointly developed by the Met Office in the UK and the Bureau of Meteorology in Australia (Bowler et al. 2006; Pierce et al. 2005). In this approach, the evolution of a field of instantaneous rain rate is modelled considering a discrete set of spatial scales. An optimal combination of nowcast and NWP outputs is then estimated in which features at scales lacking skill are replaced by synthetically generated precipitation (noise). An ensemble of equally likely outputs is then generated for current and forecast conditions consisting of a weighted blend of these components

For thunderstorm forecasting, interactive decision support systems have also been developed by a number of meteorological services; however, this is one of the most challenging applications of nowcasting techniques and this topic is discussed further in Sect. 4.4.

4.3.1.2 Tropical Cyclones

The forecasting techniques used for tropical cyclones, typhoons and hurricanes have many similarities to those used in nowcasting so for convenience are discussed here. However, the spatial scales considered are often larger and the maximum lead times possible may extend to a day or more, which is more usually the domain of Numerical Weather Prediction models.

Due to the difficulties in observing conditions over the ocean, and the strong wind speed and pressure gradients, numerical forecasting for cyclones is a challenge, particularly regarding storm intensities and precipitation (although track forecasts are often useful). This is therefore an active area for research, although multi-model and other ensemble approaches are increasingly used as part of the forecasting process (e.g. Hamill et al. 2012).

In practice, persistence-based, statistical and climatological techniques are also widely used (e.g. Holland 2012), sometimes guided by regression relationships with predictors from Numerical Weather Prediction models (statistical-dynamical models) and forecasts for the large scale circulation (trajectory models). In some countries, such as the USA, on-board and dropsonde observations are routinely made from reconnaissance aircraft to provide additional information on parameters such as wind speeds and pressures. The model outputs often include an indication of the uncertainty in position and scale at different forecast lead times; for example in the form of forecast plumes or cones of uncertainty.

Surge forecasting models are often used in combination with storm-tracking models to provide estimates of likely water levels in coastal areas. For example, the National Hurricane Centre in the USA uses a suite of hydrodynamic coastal basin models for locations in the Gulf of Mexico and along the Florida coastline and the eastern seaboard of the USA (Jelesnianski et al. 1992; http://www.nhc.noaa.gov/). These are based on a curvilinear polar grid and the grid scale and shape is adapted to resolve the influence of estuaries, bays and structures on surge propagation and overland flow. In real-time operation, the appropriate models to use are then selected depending on forecasts for the track, size and speed of the hurricane and are operated in the 24-h period leading up to the estimated time of landfall.

More generally, the World Meteorological Organisation Tropical Cyclone Programme has been influential in building capacity and sharing expertise between forecasting centres (http://www.wmo.int/). The main goals are to encourage and assist WMO Members to provide reliable forecasts of track, intensity, strong winds, surge, heavy rainfall, and floods, along with timely warnings. Other activities include advice on public awareness raising activities, risk and hazard assessments, basic data collection, and establishing national disaster preparedness and prevention measures. This has included establishing several regional specialized meteorological and tropical cyclone warning centres in the main areas affected by tropical cyclones, typhoons and hurricanes. The programme has also produced a range of guidelines and manuals covering topics such as warning message design, pre- and post-cyclone season activities, tropical cyclone naming conventions, and monitoring and forecasting techniques (e.g. Holland et al. 2012).

4.3.2 Numerical Weather Prediction

4.3.2.1 Introduction

In addition to nowcasting techniques, Numerical Weather Prediction models are another key tool in meteorological forecasting. The aim is to derive solutions for approximate forms of the mass, momentum and energy equations for the heat exchange and circulation in the atmosphere, including interactions at the land surface and – where appropriate – the ocean surface. Outputs include both directly observable quantities, such as rainfall and windspeeds, and derived variables such as potential vorticity and moisture fluxes which – as discussed in Sect. 4.4 – are sometimes useful as severe weather predictors. Solutions are typically derived using a gridded representation of the atmosphere, oceans and upper soil layers. Due to limitations on computing power, a compromise is needed between the horizontal spacing between grid points and the spatial extent of the model. Typically a global-scale model is operated at a relatively coarse grid scale (say 10–40 km), with finer scale models nested within. The global model then provides the lateral boundary conditions for the nested models, as illustrated in Fig. 4.7.

Global-scale models are typically operated by a small number of research and national centres and by WMO Regional Specialized Meteorological Centres. The outputs are then made available to other meteorological services for use in regional models. In some cases this includes operating models on behalf of neighbouring countries, such as in southern Africa where the South African Weather Service operates a region-wide 12 km resolution model and makes guidance forecasts available to countries in that region (de Coning and Poolman 2011).

The processes within each grid volume are typically parameterized using a range of statistical and other approaches, as illustrated in Fig. 4.8. This is to allow for factors such as subgrid-scale turbulence, land-atmosphere interactions, cloud microphysics, orographic influences, and radiation transfer (e.g. Stensrud 2007). Typically up to 90–100 vertical layers are used, with a closer vertical spacing for layers near to the land surface, using terrain-following coordinates.

To initialize each model run, an estimate needs to be derived for the current state of the atmosphere (e.g. Kalnay 2002; Park and Liang 2009), for which typically "…the four main challenges are (Schlatter 2000):

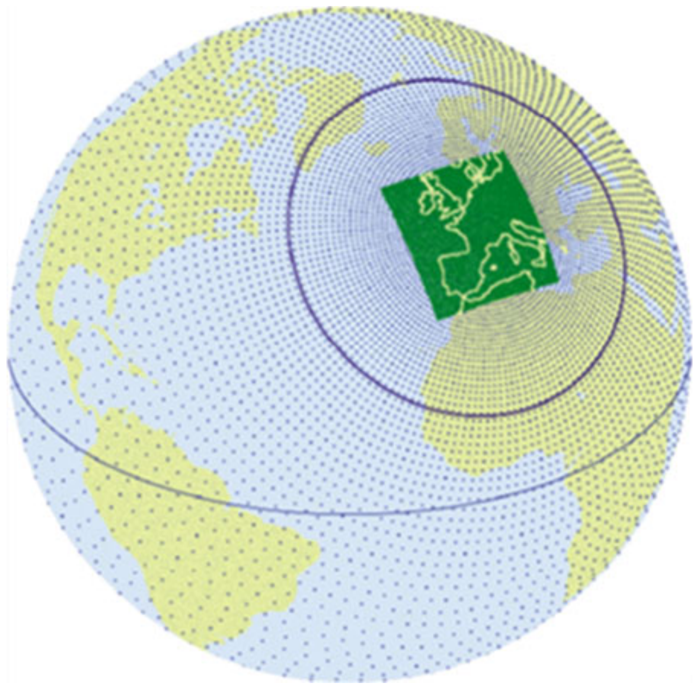

Fig. 4.7 Illustration of the Numerical Weather Prediction models operated by Météo France in 2011 at which time resolutions over France and forecast lead times were (a) Global model ARPEGE, 10 km, 12–168 h (b) Regional model ALADIN, 7.5 km, 6–48 h (c) Local model AROME, 2.5 km, up to 36 h. Note that the ALADIN model is no longer used operationally (Météo France; Carrière et al. 2011)

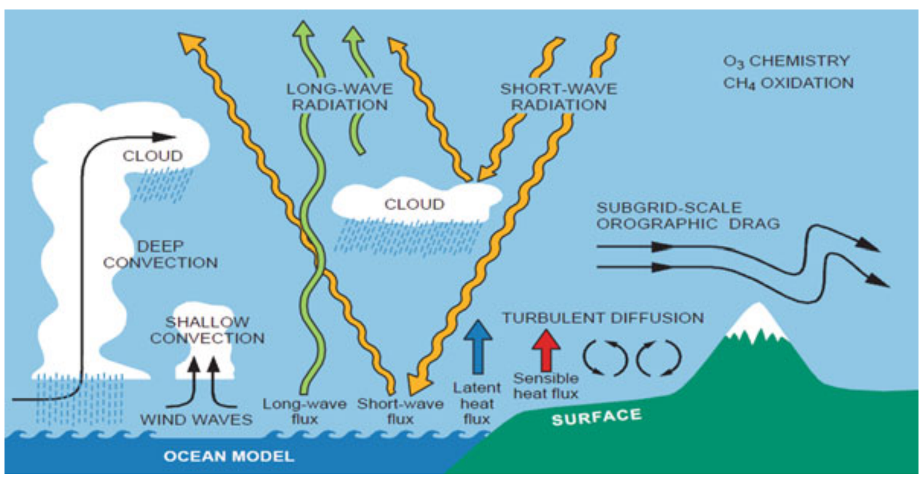

Fig. 4.8 Main physical processes represented in the ECMWF model (Persson and Grazzini 2007; Source: ECMWF)

- to generate an initial state for a computer forecast that has the same mass-wind balance as the assimilating model
- to deal with the common problem of highly non-uniform distribution of observations
- to exploit the value of proxy observations (of parameters that are not carried explicitly in the model)
- to determine the statistical error properties of observing systems and numerical model alike so as to give each information source the proper weight”

As part of the data assimilation cycle, observations are processed from a wide range of sources. For global and regional scale models, this typically includes satellite and weather station observations (land, ship, buoy), weather radar Doppler winds, lightning observations, vertical profiles from wind and radio-acoustic profilers and/or radiosondes, and air temperatures, wind speeds and humidity observations from commercial aircraft (see Chap. 2). This information is usually obtained from a centre's own observation systems, directly from satellite operators and other providers, and from data distributed globally via the WMO Global Telecommunication System (GTS). Observations are normally screened for outliers and other anomalies before use in the process.

In recent years, satellite observations have played an increasing role as the accuracy of observations has improved. Typically this provides the advantage of global scale coverage at both the land and ocean surface and has led to significant improvements in forecast accuracy, particularly in areas with limited surface observations. The types of observations and products which are used include cloud top temperatures, cloud types, vertical profiles of air temperature and humidity (or the radiances on which they are based), and estimates for wind speeds and directions at various levels (see Chap. 2).

There are many approaches to data assimilation, with 3D-Var and 4D-Var techniques currently the most widely used. For example, three dimensional variational techniques (3D-Var) seek to minimize an objective (cost) function based on the differences between the current analysis and fields based on the latest observations and the previous forecast for conditions at the current time. 4D-Var and ensemble Kalman filter techniques also allow for the differences in observation times which occur in practice (the 'fourth dimension' being time); the penalty being an increase in the complexity and computing time required. Additional procedures are sometimes included for parameters such as precipitation and cloud cover.

Since the data assimilation and modelling process is computationally-intensive, this normally places limits on how frequently forecast runs can be performed. Typically, for global- or regional-scale models, outputs are issued every 6 or 12 h, providing forecasts from the current time to 36–240 h or more ahead, depending on the type of model. Some forecasting centres also issue longer-range forecasts at less frequent intervals, such as every week or month, extending for several months ahead. Statistical models are also widely used at these longer timescales.

4.3.2.2 Ensemble Forecasts

Ensemble techniques started to be used operationally in the late 1980s and early 1990s; for example by NOAA/NCEP in the USA and the European Centre for Medium-Range Weather Forecasts (ECMWF). Since then, this approach has become standard practice in numerical weather prediction.

The ensemble outputs provide a number of possible outcomes reflecting the uncertainty in the analysis of current atmospheric conditions. In some cases, this includes a consideration of the uncertainty in model parameters and/or lateral boundary conditions. In particular, due to the unstable, chaotic nature of the atmosphere, in some conditions small errors in the initial analysis can lead to large differences in the

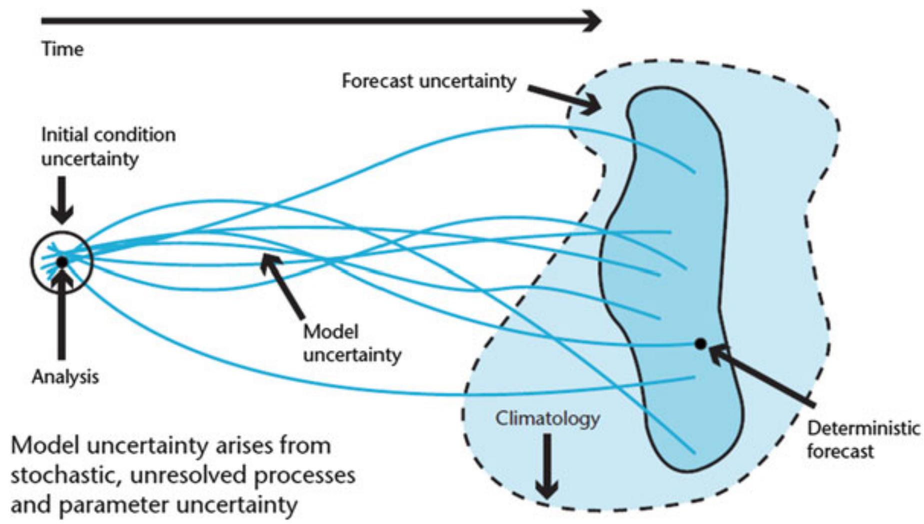

Fig. 4.9 Concept of an Ensemble Prediction System and the various sources of uncertainty that need to be represented (Met Office 2010; Contains public sector information licensed under the Open Government Licence v1.0)

resulting forecasts (e.g. Lorenz 1963), as illustrated in Fig. 4.9. Some ensemble generation schemes exploit this tendency by seeking ensemble members which will have the maximum impact on the forecast at a given lead time.

For operational use, visualization techniques provide a powerful way to interpret the resulting ensemble outputs. Some widely used formats include a page or screen of map-based ('postage stamp') outputs, plumes, box and whisker plots, and spaghetti diagrams. For example, Chap. 12 includes illustrations of a plume and a tropical cyclone strike probability map, and later sections and chapters show examples of spaghetti diagrams. Meteorological forecasters typically use these types of information to assess confidence in the model outputs and to help with producing forecasts. Some end users also use the raw or post-processed ensembles as part of their own decision-making processes; for example, in the energy, oil and gas industries and – increasingly – for flood forecasting applications (see Chaps. 5 and 12).

In some countries, selected outputs are also made available to the public. For example, in the USA, the uncertainty in forecasts for hurricane tracks has long been indicated using cones of uncertainty. Some meteorological services also routinely present ensemble or probabilistic outputs on their websites and – as discussed later – issue heavy rainfall warnings in probabilistic terms. However, there are many issues to consider with the communication and interpretation of uncertainty and these are discussed further in Chapter 12 in the context of flash flood warning applications.

For the current generation of numerical weather prediction models, typically 20–50 ensemble members are generated for each forecast run. However, due to computational limitations, these are often derived on a coarser grid scale than for deterministic forecasts, and sometimes with less frequent output intervals. Another option is to combine the outputs from global-scale models from several different forecasting centres to produce a multi-model ensemble. This also provides an indication of the uncertainty from different types of models; that is, model structural issues. This approach is sometimes also an option with local and regional models in countries where, due to the proximity to other forecasting centres, the area of interest falls within the domain of several models, such as in some parts of Europe.

4.3.2.3 Mesoscale and Convective-Scale Models

In recent years, mesoscale and convective-scale models have been implemented operationally in several meteorological centres. This is a welcome development for a number of applications, including flash flood warning.

Two key improvements in this type of model have included the adoption of a non-hydrostatic approach and a significant reduction in horizontal grid scales. Together these changes provide a more direct (explicit) representation of both the overall circulation and deep convective processes. Water phases considered typically include vapour, cloud moisture, rain, graupel, ice and snow.

A typical configuration is for a grid scale of 1–4 km with model runs every 1–6 h and outputs for up to 18–48 h ahead. With current computing facilities, typically 10–20 ensemble members are provided. In addition to new parameterization schemes, this approach has required the development of higher resolution data assimilation techniques considering types of observations not widely used in the past, such as radar reflectivity and GPS humidity values (e.g. Stensrud et al. 2009; Benjamin et al. 2010). As discussed in Chapter 12, some other possibilities for the future include phased array weather radar outputs and the use of adaptive sensing techniques.

Some meteorological centres which have adopted this approach include Météo-France (Seity et al. 2011; Box 12.2), the UK Met Office (Golding 2009) and the National Weather Service in the USA (Benjamin et al. 2010). This has generally led to significant improvements in forecast accuracy, although the gains are still being assessed. From a flood warning perspective, these are best assessed through forecast verification studies of the types described in Section 4.4.2 and Chapter 5.

For the future, many meteorological services are following the path of both improving the resolution of models, and increasing the number of ensemble members which are generated. For example, Stensrud et al. (2009) suggest that ‘a probabilistic forecasting approach is absolutely necessary for predictions on the convective scale, as the uncertainties associated with high-impact weather are large.’

4.3.2.4 Post-processing of Model Outputs

The increasing use of high-resolution models has also resulted in some changes to the approaches used for the post-processing or downscaling of model outputs. Here the aim is typically to adjust the model outputs to provide better estimates at the specific locations where forecasts are required. This step is often required because the outputs are only available on a gridded basis and are subject to various modelling errors. The types of approach which are used include:

- Analogue or Weather Matching techniques – in which a database of previous model runs and/or observations (e.g. from radiosondes) is searched to identify

similar conditions to those from the current forecast. Typically this is performed for variables which are – in principle – more predictable than rainfall (e.g. van den Dool 2007; Obled et al. 2002). An ensemble of possible scenarios is then produced using the sequence of rainfall fields observed during the selected events. Some examples of the types of predictors which are used include surface atmospheric pressure, precipitable water and geopotential height
- Statistical downscaling – regression or time series analysis techniques developed on the basis of historical observations and the results from previous model runs at the lead times of interest. One well-known example is the Model Output Statistics (MOS) approach used in the USA (e.g. Glahn and Lowry 1972; Antolik 2000; Wilks 2011), in which the types of predictor which are used, alone or in combination, include precipitable water, area averaged temperature, recent observations, and geopotential height. The parameters of the relationships are sometimes varied according to the season and other factors
- Dynamic (or dynamical) downscaling – nesting higher resolution models within the operational model which use improved physical representations and/or are better calibrated to local conditions. In some cases, simpler conceptual models are used; for example for orographic rainfall or the influence of elevation on air temperature, or single column models focussed on particular grid squares

Analogue techniques have the advantage of preserving the spatial variability in rainfall observed in a number of previous events. However the performance depends on the selection criteria and predictors which are used. Statistical techniques are simpler to apply; however the spatial and temporal relationships between variables may be altered in applying the adjustments, although this can be avoided to some extent if the same predictors are used for a number of surface variables. The coefficients also need to be regularly reviewed and possibly updated to take account of changes in models and instrumentation. Also, an archive of historical forecasts is required to develop the relationships, based on the model in its current state. Typically this is either built-up over time by storing forecast model outputs, or via a one-off reforecasting exercise (see later). Simpler techniques such as spatial interpolation of model outputs and application of elevation (height-dependent) corrections are also used.

By contrast, dynamic techniques should in principle be able to provide a better representation than both of these approaches, particularly during extreme events, outside the range of calibration. However, this is best confirmed by intercomparisons using forecast verification measures of the types described later. The performance also depends on the resolution and performance of the model used to provide the lateral boundary conditions. This approach is of course similar to the use of nested global, regional and local models in meteorological centres, and requires similar levels of expertise and computing and data assimilation capabilities. Also, since national centres increasingly use high resolution models, this has to some extent removed the need for dynamic downscaling techniques. However, there are still advantages for specific applications; for example, such as in the western USA where an orographic precipitation model is used operationally to provide estimates for watershed precipitation and snow levels in the Sierra Nevada for up to 5 days ahead (Hay 1998).

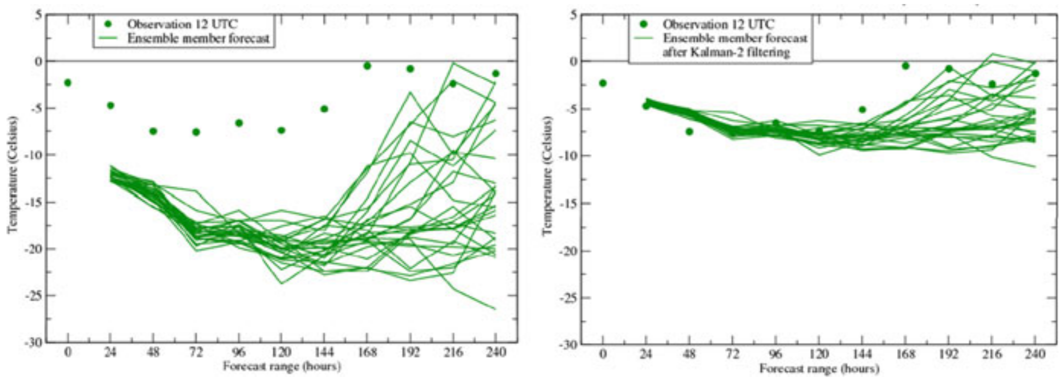

Fig. 4.10 Illustration of Kalman filter post-processing of ensemble forecast outputs. The forecast is for the 2 m air temperature for Tromsö on 12 February 2011 (*left*) and is too cold with 50%–100% probabilities of temperatures < −15°C. After the Kalman-filtered error equation has been applied (*right*), mild forecasts have hardly been modified, whereas cold ones have been substantially warmed, leading to less spread and more realistic probabilities with, for example, 0% probabilities for 2 m temperature <−15°C (Persson 2011; Source ECMWF)

Statistical and weather matching techniques also continue to be widely used and in some cases form the basis for some of the customer-specific or added-value services offered by meteorological services, such as for road-ice, aviation and agricultural advisory services.

In many cases there is also a need to post-process ensemble forecasts, particularly if the outputs are to be used quantitatively, such as in a cost loss approach in a flash flood warning system (see Chap. 12). Some reasons for an imperfect ensemble include limitations in the sampling approach used, exclusion of some sources of error (e.g. in model parameters), the limitations of sample size, and in some cases more fundamental model structural issues. This is a developing area (e.g. Jolliffe and Stephenson 2011; Wilks 2011) and one approach is to use statistical models of past forecast performance, such as ensemble versions of the model output statistics approach. Another is to use Kalman filter and related techniques (e.g. Figure 4.10). Similar approaches are increasingly used for probabilistic flash flood forecasting models and this topic is discussed further in Chapter 12.

4.4 Operational Considerations

4.4.1 Heavy Rainfall Warnings

Although there have been huge advances in computer-based forecasting techniques, the outputs are typically just one of the sources of information that a forecaster considers when issuing a severe weather or heavy rainfall warning. This is particularly the case for rapidly developing storms for which – in addition to local meteorological understanding – some other sources of information typically include:

- Decision support tools – both paper- and computer-based tools which embody past experience, using heuristic rules, indices, thresholds and other criteria for decision-making
- Forecast discussions – with colleagues, forecast users, and experts in other forecasting centres by phone, webinar, chat room etc., including flood warning and emergency response staff during potential flash flood incidents
- Incident reports – feedback on current weather-related incidents, such as heavy rainfall, strong winds and flooding, for example provided by the emergency services, government officials, 'spotters' and the public
- Observations – recent surface and atmosphere observations by satellite, weather radar, radiosondes, weather stations, GPS humidity sensors, wind profilers, and other approaches (see Chap. 2)

In larger forecasting centres, typically a range of computer-based tools is available for viewing information from different sources and for preparing synoptic charts and forecast products for different users. Often, model outputs are also available from other forecast centres, with the consistency between models, and with previous forecast runs, both important factors to consider. More generally, based on a survey of operational forecasters, Morss and Ralph (2007) note that forecasters apply their meteorological knowledge, experience and pattern recognition skills to:

- infer meteorological fields from other fields (e.g. infer winds, divergence, and lifting from upper-level pressure contours)
- select important meteorological features on which to focus their information-gathering, interpretation, and forecasting efforts [the forecast problem(s) of the day]
- interpret what different information might mean for the weather forecast

More generally, there has been a long running debate – since computer models were first introduced – on the extent to which automation will change the role of forecasters (e.g. Doswell 2004). However, Persson (2011) notes that "A decision to evacuate an area will never be made purely on the basis of automated NWP output nor is there, and might never be, one single source of automatic NWP or EPS information with a concerted message, in particular in situations threatening extreme or high-impact weather." Of course, for emergency managers, the resulting forecast or warning itself is just one piece of information to use in deciding on an appropriate response and this topic is discussed further in Chapters 6, 7, and 12 for the case of flash flooding incidents.

To help with identifying the types of conditions leading to heavy rainfall and other types of severe weather, many forecasting centres have locally applicable rules-of-thumb or procedures to assist in the forecasting process. Often these are based on the types of climatological studies described earlier in Sect. 4.2, where the aim is typically to develop scientifically-based tools to assist with issuing warnings (e.g. Doswell et al. 1996). For example, Doswell and Schulz (2006) propose that the diagnostic variables used for severe weather might be classified as follows, with each approach having its own advantages and limitations:

- Simple observed variables
- Simple calculated variables
- Derivatives or integrals (spatial or temporal) of simple observed or calculated variables
- Combined variables
- Indices

Some examples of directly observable variables which are sometimes used include air temperature, relative humidity, wind speed, hail, lightning activity, cloud base, rainfall and GPS humidity values. By contrast examples of the other categories include the Convective Available Potential Energy (CAPE), Extreme Forecast Index (EFI), helicity, lifted index, low level moisture fluxes, mixing ratio, potential vorticity, precipitable water, warm cloud depth, and wind shear, convergence and divergence. In many cases, these have been developed specifically to help with providing warnings for thunderstorms and other severe convective storms for use alone or in combination, although with varying degrees of scientific justification. Here, the mixing ratio is an example of a simple calculated variable and the CAPE an example of a combined variable.

Depending on the parameter or quantity under consideration, values can be estimated from model outputs or observations (or both approaches). Decisions are then often made on the basis of threshold exceedances. Typically these are defined either in absolute terms, or as ratios or anomalies, such as the number of standard deviations from the climatological mean, or in probabilistic terms. Methods are used alone or in combination and tend to be specific to individual regions. Other factors such as topography, elevation, and proximity to the coast often need to be considered, together with the type of storm (see Sect. 4.2). In some cases, the potential impacts are also considered, with the severity of warning or the associated message being modified depending, for example, on factors such as rainfall in the previous few days or current river levels or soil moisture conditions.

Increasingly, decision support systems are used to help with these types of analyses. For example, Box 12.1 describes a system used for the atmospheric river phenomenon described in Box 4.1 which makes use of forecast model outputs and GPS humidity, wind profiler, and weather radar observations. Ideas on key factors influencing rainfall in the Swiss Alps also underpin the analogue-based nowcasting system described in Section 4.3.

One area of particular interest for flash floods is that of thunderstorm nowcasting, and decision support tools have proved particularly useful in this application. Typically these provide an initial identification of storm locations and track based on radar reflectivity and other observations (e.g. Dixon and Wiener 1993; Wilson et al. 1998; Mueller et al. 2003; Bally 2004; Hering et al. 2008). In the user interface for the software, these then usually appear as polygons showing the estimated boundary for each storm, with arrows showing the forecast speed and direction of motion, and a backdrop of roads, rivers, topography and other features. In some systems, observations for wind speeds, gust speeds, hail and rainfall are shown along the estimated storm track.

Typically forecasters then have the option to adjust cell locations, boundaries and tracks and define new cells or delete erroneous values. Analyses can then be repeated based on these decisions. To save time, templates are provided in some systems to assist with the automated generation of text-based and graphical warning messages (e.g. Deslandes et al. 2008). However, as for other types of severe weather prediction, usually techniques are not fully automated and "….some examples of areas where forecasters can add value (Brovelli et al. 2005) include:

- Set associated significant weather attributes for objects, or monitor their automated initialisations: wind gusts, hail risk, rain accumulation
- Indicating a decay/growth tendency and associated significant weather
- Set non-linear tendencies on location, duration, attributes …
- Create objects for convective phenomena missed or not anticipated by the CONO
- Merge CONO objects of similar behaviour when necessary"

Here, the term Convection Nowcasting Objects (CONO) describes the individual storms ('objects') identified and displayed graphically by the system.

In Finland, another development has been to investigate the potential for combining information on thunderstorms with reports of emergency incidents, logged via emergency call centres at a national scale (Halmevaara et al. 2010). In this approach, an automated procedure identifies possible linkages between incidents and storms, based on the size and track of objects, and alerts forecasters to potentially dangerous or damage-causing cells (e.g. Fig. 4.11) for further investigation; for example that the incidents logged were definitely rainfall-related. Information can also be displayed on the time and type of the incident together with a free-form verbal description. Techniques like these all have the potential to help forecasters to issue more accurate and timely warnings for thunderstorms and the associated rainfall, and so are of great interest for flash flood warning applications

4.4.2 *Forecast Verification*

Forecast verification studies are widely used to help to understand the uncertainties and limitations in weather forecasting models, and the ways in which they can be improved. However, a distinction is often made between administrative, scientific and economic reasons for verification (e.g. Jolliffe and Stephenson 2011); for example, for use in internal monitoring and reporting, research and development, and investigating the value of forecasts to end users (economic or otherwise).

Most meteorological services have verification programs in place and in some cases issue publicly available reports on performance at regular intervals. This can include information on the reliability of the forecast delivery process itself, such as whether forecasts are issued on time and consistently year-round. After reporting for

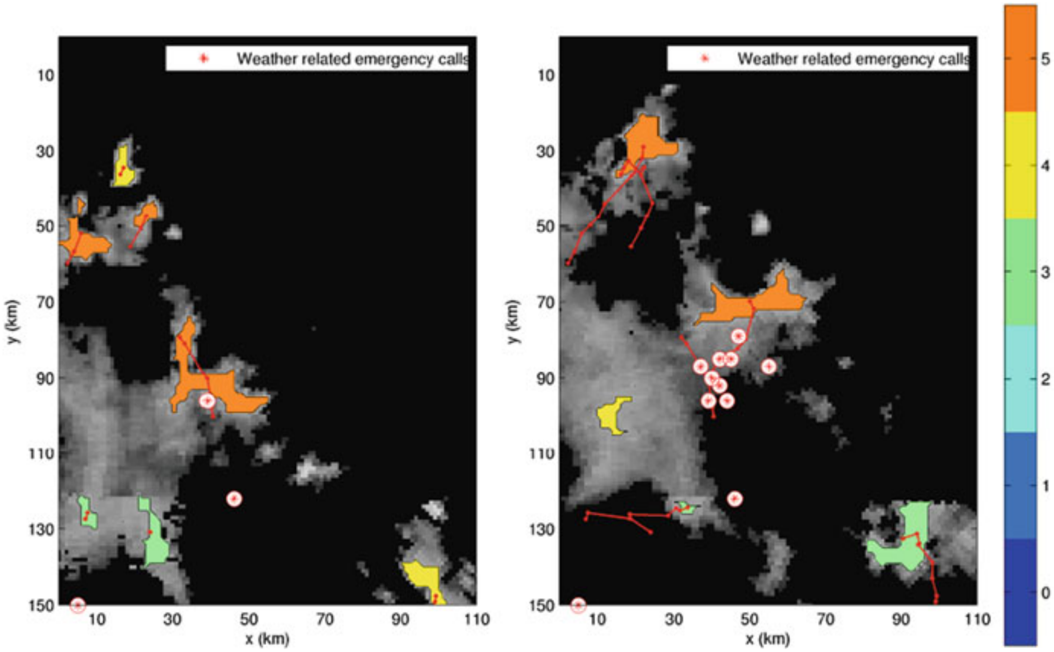

Fig. 4.11 Illustration of a convective cell decision support tool under development at the Finnish Meteorological Institute and Aalto University School of Science and Technology. The figure shows the severity classification on 14 August 2007 at 1420 UTC and 1445 UTC; a day on which several severe thunderstorms occurred. *Red lines* denote cell tracks and coloured polygons identify convective cells using a scale of 0–5, where 5 is the most severe. The severe storm in the centre of the display caused several emergency calls, which are marked as *red stars* in the images (Rossi et al. 2010)

a few years, it is often possible to see how forecast performance has improved over time and how it compares with the outputs from other forecasting centres.

Most verification schemes compare model outputs with ground observations, either at a point or interpolated onto a grid. Some examples of the approaches which are used include:

- Categorical statistics – statistics derived over many events based on the crossing of critical thresholds, using measures such as the Probability of Detection (POD) and False Alarm Ratio (FAR)
- Magnitude and timing errors – statistical comparisons of observed and forecast values such as the maximum, minimum, bias, root mean square error, time of maximum and correlation coefficient
- Skill scores – measures which express the additional skill provided by the forecast compared to an unskilled forecast, such as one based on climatological values, as a ratio to the equivalent value for a perfect forecast

Chapter 5 provides more detail on these techniques in the context of forecast verification for flood forecasts, and includes an example of a contingency table used for calculating categorical statistics.

For the verification of rainfall forecasts, typically the main approach is to compare the outputs with radar rainfall observations or spatially averaged raingauge estimates. Usually it is advisable to consider a range of measures, tailored to the application, and to estimate values at a range of forecast lead times, thereby providing an indication of the reductions in forecast skill or accuracy with increasing lead time. For example, Murphy (1993) identified the following three characteristics of a good meteorological forecast:

- Consistency – the correspondence between forecaster's judgements and their forecasts
- Quality – the correspondence between the forecasts and the matching observations
- Value – the incremental economic and/or other benefits realized by decision makers through the use of forecasts

Here, forecast quality was defined to include the aspects of bias, association, accuracy, skill, reliability, resolution, sharpness, discrimination, and uncertainty. The topics of forecast value, reliability, resolution and sharpness are also discussed briefly in Chaps. 5 and 12 in the context of probabilistic flood forecasting.

For ensemble forecasts, measures such as the Continuous Ranked Probability Score and Relative Operating Characteristic are widely used. Typically these types of measures express the correspondence of probability distributions and threshold-crossing performance with that indicated by long-term observations for a location or region. In part due to the move towards higher resolution models, spatial verification techniques are also increasingly used. These place less emphasis on point-to-point or grid-to-grid comparisons, and instead borrow ideas from fields such as image and signal processing to determine whether the main characteristics of fields are captured (Rossa et al. 2008; Jolliffe and Stephenson 2011). Some examples of the methods which are used include neighbourhood ('fuzzy'), object-oriented and scale decomposition approaches.

Another key tool in forecast verification is the reforecasting or hindcasting of model outputs. In this approach, the forecasting model is run off-line in a form representative of its current operational configuration, including the data assimilation component. Forecasts are then reconstructed for periods of several years or more. Where – as is usual – there have been changes in the types and location of instruments over time, adjustments usually need to be made to allow for the impacts on model performance. Also, account needs to be taken of changes over time in the hardware and signal processing techniques used for weather radars and satellites. For the study of extreme events, such as flood-generating storms, periods of several decades would ideally be considered to sample a wide range of events.

Reforecasting exercises have many uses in addition to forecast verification although are potentially a major undertaking, even if just considering reconstruction (reanalyses) of past atmospheric conditions. To date the focus has been on reanalyses and these have been performed by a number of meteorological centres (e.g. Dee et al. 2011; ECMWF 2007) and in some cases the simulations date back to the 1940s or before. However, reforecasts are potentially particularly useful for evaluating ensemble forecast outputs and how well they match past (climatological) probabilities, and for calibrating analogue and statistical post-processing schemes. For example, Hamill et al. (2006) note that for '….many difficult problems such as long lead forecasts, forecasts of rare events, or forecasts of surface variables with significant bias, a large training sample size afforded by reforecasts may prove especially beneficial'. The results are also useful in the development of flash flood forecasting models when a rainfall forecast input is used (see Chap. 12).

More generally, forecast verification plays a key role in driving improvements to meteorological forecasting models and there is an extensive literature on this topic. Many of the techniques discussed here are also used for the verification of satellite, weather radar or raingauge observations and when using multi-sensor precipitation estimates. For further reading on the approaches which are used, some comprehensive reviews include the reports, books and review papers by Stanski et al. (1989), Jolliffe and Stephenson (2011), Casati et al. (2008), Wilks (2011), and World Meteorological Organisation (2008).

4.4.3 Forecast Delivery

Most meteorological services use a wide range of methods for issuing forecasts, and options include television and radio broadcasts, websites, and direct emails and text messages to end users. Forecasters may also be available for discussions about extreme weather conditions, particularly to civil protection and emergency response staff. Well-defined procedures are usually in place for alerting these and other key groups in case of severe weather or heavy rainfall forecasts.

The formats used for warning messages vary widely, and range from text-based descriptions to interactive internet-based maps and animated sequences for rainfall and other variables. In recent years, mobile phone applications have become increasingly available and are a popular way for receiving forecast information. Typically users are able to specify the locations or areas of interest, viewing forecast and radar information on a map and list basis. With GPS-enabled smartphones, forecasts can also be tailored to a user's current location.

Probabilistic rainfall thresholds are also increasingly used, taking account of both probability and consequences, with the aim to offer tailor-made warnings to flood warning services and other expert users. This topic is discussed further in Chapters 8 and 12. Chat rooms, blogs, webinars and social media are also increasingly used to provide regular updates during emergencies, and to allow a two-way flow of information between forecasters and end users (see Chap. 6).

For flash flooding applications, another common requirement is to provide the raw or post-processed forecast outputs for use as inputs to flood forecasting models. This often requires establishment of a secure transmission route – resilient to power cuts and other problems during heavy rainfall and flooding events – and establishment of round-the-clock (24/7) support and service level agreements. A system of version control also needs to be established, so that users are aware of any significant changes to the meteorological forecasting system or algorithms which could impact on flood forecasting model performance. Forecasts also need to be archived for future use in post-event analyses, model calibration studies and operator training exercises.

For example, for the latest generation of meteorological models, transmission is typically required of both probabilistic nowcasting outputs and ensemble mesoscale or convective-scale model outputs. A typical scenario would therefore be to send nowcast outputs every 5 min consisting of 20 ensemble members at a grid resolution of 1 km and forecast interval of 5 min for a lead time of 6 h. The NWP component would then add 10–20 ensemble members for each parameter of interest (typically rainfall and air temperature) every hour for 24–36 h ahead at hourly intervals at a grid scale of 1–4 km. When a multi-model approach is used, model outputs are also required from other forecasting centres or via a central agency which performs this aggregation task.

These requirements typically result in large data volumes, but are entirely manageable with modern communication networks and forecasting and data management systems. Another issue is how – and whether – to build forecaster expertise into the process. However, in flash flood situations, there is limited time to provide inputs although this is possible with some of the latest thunderstorm nowcasting systems described earlier.

As discussed in Chapter 12, there is also considerable research underway to develop interactive modelling systems which allow a forecaster to review model outputs and initiate new model runs; for example with improved initial conditions, higher resolution in the areas of greatest interest, and better definition of atmospheric features (fronts, rainfall areas etc.). Often there is also scope for closer collaboration between meteorological and hydrological forecasters in interpreting the outputs from flood forecasting models before a flash flood warning is issued, thereby bringing more meteorological expertise into the forecasting chain. This can be particularly important for flash floods and some possible ways to facilitate this process include establishing joint hydrometeorological operations centres (either permanently, or during flood emergencies), regular phone- and web-based discussions as events develop, temporary secondment of staff between centres, establishing hydrologist posts in meteorological centres (and vica versa), and joint training and emergency response exercises.

4.5 Summary

- Rainfall forecasts provide the potential to issue flash flood warnings earlier than is possible when using observations alone, giving people more time to take actions to reduce the risk to life and property. The main ways in which forecasts are used include as a guide to issuing flash flood advisories and heavy rainfall warnings and as inputs to flash flood guidance techniques and flood forecasting models
- Most flash floods arise from heavy rainfall and an understanding of flash flood climatology helps with developing tools to identify the risk of flooding and the likely timescales involved. The causes vary widely by location but include thunderstorms, cutoff lows, mesoscale convective systems, frontal systems, monsoons

and tropical cyclones. In recent years, atmospheric rivers have also been identified as a significant cause of heavy rainfall and flooding in some coastal areas

- For lead times of up to about 6 h, nowcasts are widely used. These extrapolate the motion of areas of rainfall observed with weather radar or satellite, and in some cases allow for the growth, splitting and decay of storm cells. Other sources of information are increasingly used to improve the initialisation of model runs and to guide the advection process. These include observations from raingauges, lightning detection systems and wind profilers, and the outputs from Numerical Weather Prediction models. At longer lead times, similar techniques are used for forecasting the development of tropical cyclones, hurricanes and typhoons
- In recent years, there has been a step change in the resolution of operational Numerical Weather Prediction models. As a result, the outputs are now much closer to the scales of interest for flash flooding applications. For example, mesoscale and convective-scale models are increasingly used operationally with hourly forecast runs and outputs at grid scales of 1–4 km. This has required the development of new approaches to data assimilation, including the use of weather radar reflectivity and GPS-based precipitable water observations
- However, despite these advances, post-processing techniques are still widely used to improve the accuracy of forecasts, and include analogue (weather matching), statistical and dynamic techniques. Some typical applications include downscaling model outputs to the locations or areas of interest, and calibrating the probabilistic content of ensemble forecasts for use in flash flood and other applications
- Meteorological forecasters play a key role in issuing heavy rainfall warnings and use information from many sources, including forecasting model outputs, local knowledge, observations and discussions with colleagues. Much research has also been performed into the thresholds, indices and other indicators to use when deciding whether to issue warnings. Increasingly this has led to the development of decision support tools to use as part of this process, particularly for warnings related to thunderstorms
- Forecast verification plays a key role in assessing the quality of forecasts and helping to identify areas for improvement. For rainfall forecasts this includes a range of categorical statistics and skill scores. The move to higher resolution models has also placed an increasing emphasis on spatial verification techniques. Reforecasting or hindcasting exercises play a valuable role in these types of studies, particularly regarding the verification of extreme events and probabilistic techniques
- In flash flood warning applications, the main ways in which rainfall forecasts are made available to flood forecasting staff include discussions with meteorological forecasters, the dissemination of publicly-available or tailor-made forecast products, and delivery of the raw ensemble model outputs for use in flood forecasting models. In the latter case some issues to consider include data volumes, service level agreements, version control and ways to make use of forecaster expertise in the process

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Chapter 5
Flood Forecasting

Abstract Flood forecasting models typically provide estimates of future levels and flows. These outputs can help with providing earlier warnings of the likelihood of flooding than is possible from observations alone, and with interpreting complex situations. The main types include data-driven, conceptual and physically-based rainfall-runoff models and hydrological and hydrodynamic flow routing components. Data assimilation techniques are also widely used, and forecasts are increasingly based on a probabilistic or ensemble approach. This chapter describes the background to these techniques and to some of the considerations in using flood forecasts operationally, such as the decision-making process when interpreting outputs, forecast verification techniques, and the role of forecasting systems.

Keywords Rainfall-runoff • Flow routing • Hydrological • Hydrodynamic • Data assimilation • Forecast interpretation • Forecast verification • Forecasting system

5.1 Introduction

Flood forecasting models have the potential to help to extend the lead time provided when issuing flood warnings, and to produce additional information to improve decision-making. This then provides the public and civil protection organisations with more time to prepare for flooding, ideally with less chance of false or missed alarms. With sufficient advance warning, it is sometimes possible to reduce the extent of flooding through flood fighting activities, protecting individual properties, and operating river control structures.

The main inputs which are required to a river forecasting model typically include river level or flow observations and raingauge, weather radar or satellite data. Information is typically received by telemetry although manual observations are used in some systems. Other types of observations are sometimes required to support the operation of reservoir, snowmelt and other sub-models. Rainfall forecasts are also increasingly used to extend lead times further, and forecasts for other variables

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are sometimes required, such as of air temperatures for use in snowmelt models. Some of the earliest types of flood forecasting models to be used operationally included:

- Correlations – relationships between peak levels or flows at gauging stations along the same river, with an indication of likely travel times, and sometimes with a range of curves or equations for the same reach to allow for factors such as snowmelt, antecedent conditions or tributary inflows
- Rate of rise approaches – methods which extrapolate the increase in river levels at an individual gauging station to indicate if flooding thresholds are likely to be exceeded, using either fixed rate-of-rise values or variable estimates derived from real-time observations
- Time of travel methods – maps or tables which show indicative estimates for the time delay between flood peaks in different parts of a catchment, and possibly the delays between rainfall and peak flows, based on historical observations or hydrological modelling studies

These techniques are still used in community-based flood warning systems and as a backup measure and 'reality-check' for the outputs from more sophisticated models. Rainfall depth-duration thresholds are also widely used for an initial alert (see Chaps. 8 to 11) together with flash flood guidance methods (see Chap. 8). However, these approaches, although important, have increasingly been complemented by more complex types of models, for which the main types include:

- Rainfall-runoff (or hydrologic) models – which provide estimates for future river flows or surface water runoff based on rainfall observations and (in some cases) rainfall forecasts. The main types include data-driven, conceptual and physically-based models, operating on a lumped, semi-distributed or distributed basis, depending on the type
- Flow routing models – which translate river levels or flows at one location to others further downstream, sometimes allowing for complicating factors such as tidal influences and operations at flow control structures. The main types are hydrological and hydraulic (or hydrodynamic) models

Generally with these types of model there is a trade-off between the lead time provided, the forecast accuracy and the uncertainty in outputs. Typically rainfall-runoff models provide longer lead times but at the expense of higher uncertainty than with flow routing models. For both types, whenever possible forecasts are adjusted based on comparisons with real-time observations. This process, called real-time updating or data assimilation, is a key feature which distinguishes flood forecasting models from their off-line counterparts, and often leads to improvements in forecast performance. Probabilistic and ensemble techniques are also increasingly used to provide an estimate of the uncertainty in model outputs.

The choice of approach usually depends on a wide range of factors, as illustrated in Table 5.1 and Box 5.1 for a river forecasting application. Similar principles apply to other types of flash floods. In practice, many of these factors are important and often a risk-based approach is used as a guide to the level of complexity required,

Table 5.1 Some examples of factors which typically influence the choice of modelling approach for a river flood forecasting model

Category	Item	Description/comment
General	User requirements	Subject to budgets and technical feasibility, some issues to consider include topics such as the locations where warnings are required (forecasting points), the warning lead times ideally required, and the amount of detail to be provided by the model: for example, just a general alert to a region, or site-specific forecasts for river levels, or real-time inundation maps? Requirements are typically determined through discussions with end users and reviews of policy, procedures etc.
Technical issues	Catchment response times	The typical response time between rainfall and flooding at areas at risk provides an indication of the maximum warning time which is possible, unless rainfall forecasts are used. In some cases, the effects of factors such as reservoirs, lakes, and flow control structures need to be considered
	Flood risk	Risk is normally defined as a combination of probability and consequence, and risk-based techniques are widely used in flooding applications to prioritise both investment decisions and operational improvements
	Probabilistic forecasts	Is a single-valued (deterministic) forecast required, or an ensemble or probabilistic estimate allowing for the uncertainty in initial and boundary conditions and/or model parameters?
	Catchment characteristics	What are the main factors that influence the extent and magnitude of flooding in a catchment, particularly at proposed forecasting points? Possibilities include lakes, wetlands, artificial influences (reservoirs, control structures etc.), soil type, geology and other factors
Data issues	Historical records	The choice of model is often constrained by limitations on the quality, completeness and length of records available for model calibration and validation, as discussed in later sections
	Meteorological forecasts	The spatial resolution, maximum useful lead time and forecast update intervals are key factors to consider. Also whether a deterministic or ensemble input is to be used
	Telemetry	As discussed in Box 5.1, the model design is often strongly influenced by the locations, quality and frequency of the real-time data available for input, data assimilation and post-processing
Institutional issues	Budgets/staff resources	The costs associated with model development typically include software licences, staff time, data purchases, and other factors. If a hydrodynamic model is used, river channel survey and digital terrain data may be required
	Forecasting system	Some forecasting systems place limitations on the types of models available, although open-architecture systems are becoming increasingly common (see later) and allow a wider choice from several vendors. However not all systems are able to handle grid-based or ensemble inputs (if required) and there may be implications for model run-times and data volumes
	Organisational issues	Past experience with particular types of models is often an important factor in model selection; in particular whether better results are likely to be obtained by an experienced modeler using a simple, well-understood model, compared to a less experienced modeler using a type with which they are not familiar? Many organisations also have preferences or approved lists for model types and suppliers

sometimes supported by cost-benefit or multi-criteria analyses. For example, a simpler model may be more suitable for a rural area with a few isolated properties than for a major city with thousands of people potentially at risk. The following sections discuss these modelling techniques further and some related operational issues, such as the interpretation of forecasts, forecast verification techniques and the role of flood forecasting systems. Chaps. 8 to 11 provide further examples of the applications of these techniques for specific types of flash floods.

Box 5.1 Site-Specific Modelling Considerations (Rivers)

Site-specific forecasts provide estimates of future river levels and/or flows at a given location, often called a forecasting point. This contrasts with the more general alerts provided by rainfall alarms and flash flood guidance methods. Some typical locations for forecasting points include:

- Areas at risk from flooding (towns, cities etc.)
- Critical infrastructure (power stations, hospitals etc.)
- River control structures (flood gates, tidal barriers etc.)
- River gauging stations (for real time evaluation and updating of forecasts)
- Reservoirs (to assist with flood control operations)

Often a maximum lead time is specified beyond which the uncertainty is too high for the outputs to be operationally useful.

In developing a model, the usual aim is to represent those components in the hydrological cycle (Fig. 5.1) which are significant in terms of flooding; however each forecasting problem needs to be considered on a case-by-case basis. For example, although groundwater influences are usually excluded from flood forecasting models, high groundwater levels sometimes have a major influence on runoff, causing flooding for much lower rainfall depths and durations than normally expected. Some other general principles (Environment Agency 2002) which can help to minimize the uncertainty in outputs include ensuring that:

- the selected model has the appropriate functionality and structure for the forecasting problem being considered
- the assumptions in the model are understood and documented and available in real-time use
- the model is calibrated using reliable, quality controlled data of the same types which will be used in real-time
- the calibration is performed by staff with the necessary skills
- real-time updating is used with an appropriate updating procedure when the data are reliable enough to support such an approach

Models should also be tested using extreme rainfall and/or flow inputs to determine if they continue to provide plausible results and to operate without

(continued)

Box 5.1 (continued)

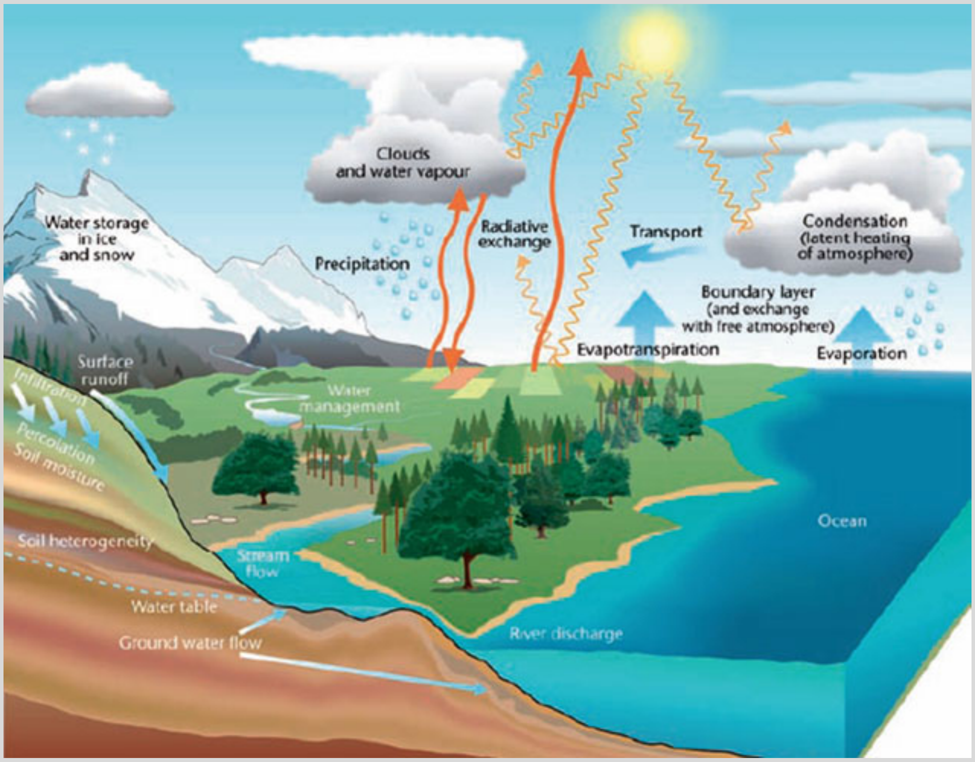

Fig. 5.1 The Global Hydrological Cycle (Met Office 2010; Contains public sector information licensed under the Open Government Licence v1.0)

failure (particularly for hydrodynamic models). As indicated, where possible forecasts should be updated using real-time data from telemetered river gauges, which limits the number of locations in a river catchment where site-specific forecasts can be provided. This is because the uncertainty is considerably higher when since data assimilation cannot be used. As a result forecasts for ungauged locations tend to be used only if a verification exercise shows the outputs to be operationally useful; for example as is sometimes the case for intermediate node locations in a hydrodynamic model. However, for the hydrological component, distributed rainfall-runoff models provide another option for ungauged catchments and are discussed in Sect. 5.2. More generally, some options for providing site-specific forecasts include:

- A single rainfall-runoff model to the forecasting point of interest, operated using real-time raingauge and/or weather radar observations and possibly rainfall forecasts, or possibly a flow routing model from an upstream gauge if this would provide sufficient lead time
- A network of rainfall-runoff models – with the same rainfall inputs as above - providing forecasts at one or more upstream river gauges, with a flow routing model (or models) used to translate flows downstream to the

(continued)

Box 5.1 (continued)

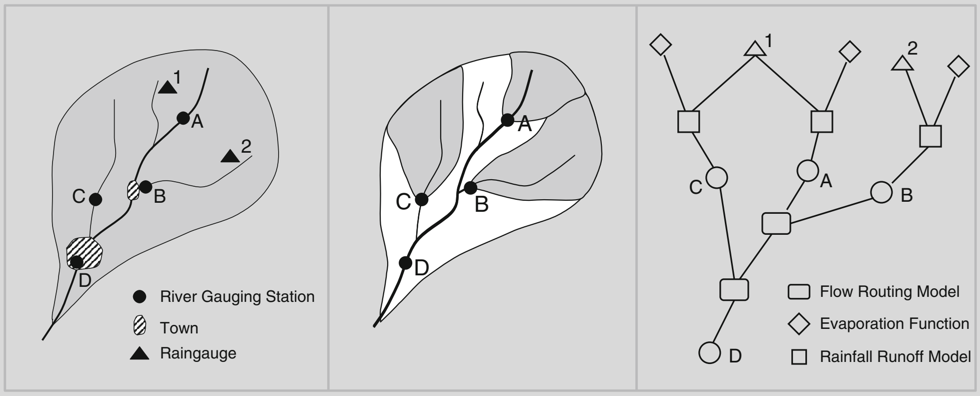

Fig. 5.2 Illustration of a possible integrated catchment model configuration for the catchment shown on the *left*. The *centre image* shows the gauged (*shaded*) and ungauged (*unshaded*) catchment areas which need to be considered whilst the image on the *right* shows one possible schematic for the information flow in the model (for convenience excluding the ungauged inputs) (Adapted from Sene 2010)

forecasting point(s) of interest, and additional rainfall-runoff models for any ungauged catchment areas

Figure 5.2 provides an illustration of the second of these options, which is often called an integrated catchment model. This also shows how the individual model components typically need to be tailored to the river telemetry sites in the catchment (or, at least, those which provide real-time data of sufficient quality and reliability for use in the model).

Some other factors which can influence the choice of approach include the relative magnitudes of the inflow contributions from subcatchments and the size of the catchment relative to typical storm scales. For example, in small catchments there may be little benefit from introducing the extra complexity of an integrated catchment model. However, one of the advantages of an integrated model is that it is able to account – to some extent – for the variations in rainfall around a catchment and the resulting influences on flood flows. Also, if there are several forecasting points in a catchment, there are sometimes operational and other benefits in using a model of this type, rather than developing separate models for each location. Sub-models for additional features can also be included if required, such as for operations at reservoirs and flow control structures.

If an integrated catchment model is used, then for ungauged areas some options for estimating the inflows include the following approaches:

- Parameter transfer – identifying nearby gauged catchments with similar characteristics and using the parameter values from models for those areas;

(continued)

Box 5.1 (continued)

alternatively, using the parameters from a model for a gauge further upstream or downstream from the location of interest (if available)

- Regionalisation of parameters – developing regression or other relationships between key parameters and a selection of catchment characteristics based on models developed for a number of hydrologically similar catchments
- Scaling – adjusting the flows for a nearby catchment using a scaling factor based on catchment area and possibly other variables, such as the mean annual rainfall, including a suitable timing difference if appropriate

Some further fine tuning is then normally required to improve the calibration of the model at each forecasting point. Where it is unclear which technique to use, as in all aspects of model development it is useful to compare the outputs from different approaches. However it is worth noting that success with regionalization techniques is usually very dependent on the model type, and typically requires calibrated models for many catchments if this type of study has not been performed previously.

Another key consideration is the catchment response time to the forecasting point(s) of interest. As discussed in Chaps. 1 and 7, in practice the warning lead time which can be achieved is sometimes much less than this due to the time delays in receiving data, running models, taking decisions and issuing a warning. One approach to assessing whether it will be possible to provide sufficient lead time is therefore to estimate the magnitude of these delays relative to the catchment response time. If the estimated value is insufficient then some possible options include reviewing whether the monitoring, forecasting, warning and response process can be streamlined and/or using rainfall forecasts to provide additional forecast lead time (provided that verification studies show the performance to be acceptable). In particular, there may be opportunities to work with communities, civil protection authorities and other groups to see if it is possible to make some aspects of the process more efficient. Of course, the concept of a characteristic catchment response time is only a guide and analyses of previous flood events often show a wide range of time delays between rainfall and the onset of flooding. These typically arise from event-specific differences in rainfall distributions, antecedent conditions, artificial influences and other factors. In practice, a mean or median value is often assumed, or a minimum value from a high flow event as a worst case.

If this type of analysis suggests that, following receipt of a warning, the time available for response is unlikely to be sufficient, or that the forecast accuracy is likely to be poor, then one conclusion might be that a site-specific model is not viable without installing additional monitoring equipment or waiting for improvements to the accuracy of rainfall forecasts. However all options should be explored before taking this major decision. Another key question is the extent to which forecasts would be used operationally in taking decisions to issue warnings, and this topic is discussed further in Sect. 5.3.1 and Chapters 8 to 11.

5.2 Forecasting Techniques

5.2.1 Rainfall-Runoff Models

Rainfall-runoff or hydrologic models translate observed or forecast rainfall values into estimates for future river flows, and normally fall into one of the following categories (e.g. Fig. 5.3):

- Conceptual models – which represent a river catchment as a series of interconnected conceptual stores, which fill, overflow, drain and empty based on the rainfall inputs and the estimated losses. Typically, various combinations of surface runoff, infiltration, interception, evapotranspiration, soil moisture, percolation and baseflow components are included, using a single 'lumped' rainfall input for the whole catchment. Sometimes additional sub-models are included such as for reservoirs, the abstractions and discharges related to water supply, and simple flow routing components

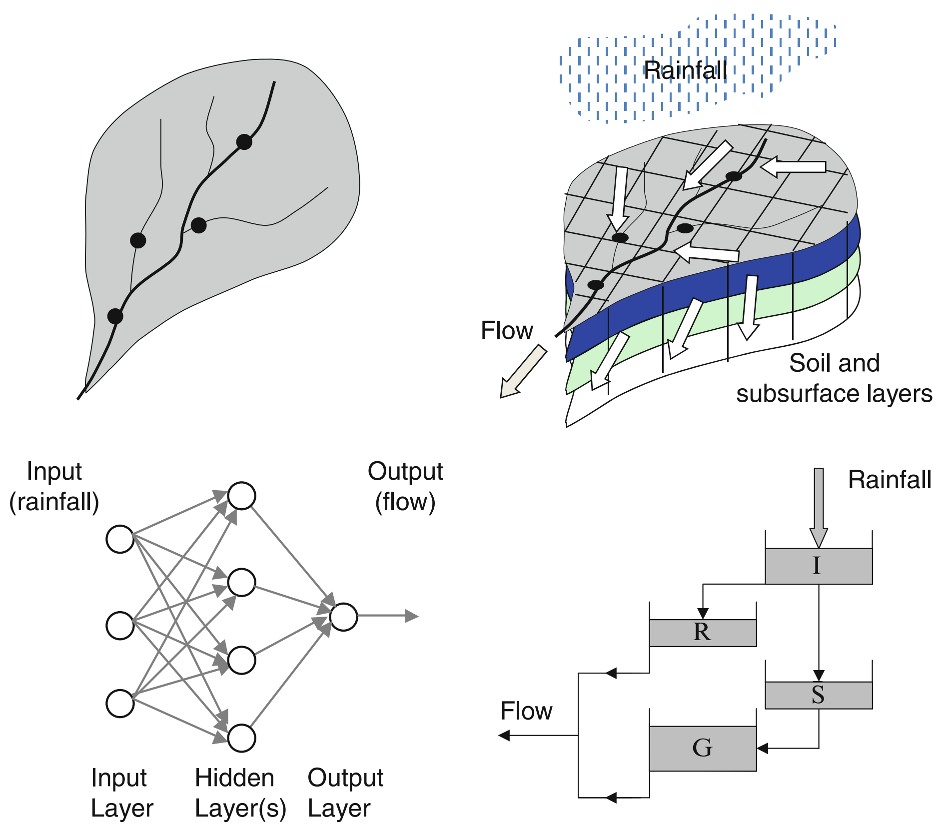

Fig. 5.3 Some simple examples of physically-based, conceptual and data-driven rainfall-runoff model representations of a catchment. From the top left clockwise: plan view of the catchment; physically-based model with three soil and subsurface layers; conceptual model with interception, soil, surface runoff and groundwater stores; artificial neural network model. Note that for convenience the evapotranspiration components are not shown (Sene 2010)

- Data-driven models – techniques such as transfer functions and artificial neural networks which represent the translation of rainfall to flows or levels by one or more pathways, but without necessarily requiring a physical interpretation of the underlying mechanisms. Some alternative names are black box or data-based models
- Physically-based models – models based on partial differential and other equations for the surface runoff production within grid cells, the drainage to deeper layers, and the translation of surface and sub-surface flows between cells. Typically these make use of grid-based inputs for rainfall and other forcing variables and spatial datasets for land use, topography, river drainage networks and other features. Some alternative names include process-based, deterministic or distributed models

For conceptual models, the main data requirements are typically for catchment averaged rainfall values and potential evaporation (or evapotranspiration) estimates. The sensitivity to the evaporation inputs varies widely between model types and in some cases an assumed seasonal variation is sufficient. Where a more accurate estimate is required, Penman and Penman-Monteith approaches are sometimes used based on measurements or estimates of air temperature, wind speed, humidity and radiation; however, as discussed in Chap. 3, real-time observations of evaporation or evapotranspiration are rarely used since it is often difficult to obtain reliable estimates.

Conceptual models are typically calibrated based on a comparison of observed and forecast flows at river gauges over a number of historical events. Indicative ranges for parameters for similar types of catchments are sometimes available from regionalization studies although, as indicated in Box 5.1, the viability of this approach depends on the type of model. In many cases, a common finding is that only a small number of parameters have a significant influence on model performance at high flows, although the extent to which this applies depends on the specific model used. As discussed in Sect. 5.3.2, a wide range of verification criteria are potentially available and tend to emphasis different aspects of the model performance. There may therefore be advantages in evaluating a model using several criteria, and perhaps formalizing this in a multi-objective approach.

For data-driven models, by contrast, usually there are fewer preconceptions about the number of parameters, the parameter values, or the data inputs required, and sophisticated time series analysis techniques are often used to identify the optimum data sources, model structure and coefficients. However, in some cases, this process is guided by ideas about the underlying modes and characteristic timescales inherent in the catchment response (e.g. Young and Ratto 2009). Models are usually event-based, so for real-time operation require a suitable starting condition to be provided, such as the current flow or a measure of catchment state. In some approaches, models are identified and optimized directly for the lead times of interest for flood forecasting, and combine data assimilation and uncertainty estimation components, and these are all features of interest for flash flood applications.

For physically-based models, ideally the calibration would be based entirely on model parameters derived from laboratory or field experiments. For example, it is sometimes possible to define typical values based on catchment topography, soil types, channel characteristics, and other factors. However, in practice these predefined values are often used as a starting point for the calibration, with some further fine-tuning required based on comparisons of observed and forecast flows at gauge locations within the area covered by the model. For real-time use, another consideration is that models of this type are typically 'data hungry' in the sense of requiring multiple sources of data at a high spatial resolution.

Different combinations of these various approaches have also been developed; for example, physical-conceptual models which combine conceptual runoff production and cell-to-cell routing components and operate on a gridded basis, and data-driven models which include pathways to represent typical surface and groundwater flow response timescales, which are sometimes called hybrid metric-conceptual models, or grey box models. In some applications, such as for arid zones and urban areas, the sub-surface component often assumes less importance and in some cases is even omitted; for example where it can be assumed that floods will usually be caused by rainfall falling on a dry, sun-baked surface. However detailed investigations of the relationships between rainfall, runoff and catchment conditions are normally required before these types of assumptions are made.

For all model types, once a model has been calibrated, a validation period different to the calibration period is normally chosen to assess the model performance. A systematic programme of forecast verification is then established once the model is in operation (see Sect. 5.3). Generally it is important to calibrate models using the same sources of data as will be used in real-time operation; for example, to use an archive of weather radar observations if radar rainfall observations are to be used in real-time. For rainfall forecasts, some additional post-processing or downscaling of outputs may improve the forecast accuracy, as discussed in Chap. 4. Also, for some types of models, such as most conceptual models, catchment averaged estimates of rainfall are required as inputs. When using gridded inputs from weather radar, satellite observations or meteorological forecasts, these are easily calculated. By contrast, when using raingauge inputs, many different approaches are used, including Thiessen polygon, inverse distance and Kriging techniques, and Chap. 2 provides more background on this topic.

More generally, there is much debate in the hydrological literature about the relative merits of these different modelling approaches (e.g. Arduino et al. 2005; Todini 2007; Sivakumar and Berndtsson 2009; Beven 2012). For example, some typical discussion points include the pros and cons of scaling-up field-scale processes to the grid scale compared to using sub-grid parameterisations, and the use of simpler parsimonious model-types compared to more detailed physically-based (but possibly over-parameterised) approaches.

There have also been several international intercomparison experiments specifically for real-time flood forecasting models (e.g. World Meteorological Organisation 1992, European Flood Forecasting System 2003) and more generally for distributed rainfall-runoff models and ungauged basins (e.g. Reed et al. 2004, Andréassian et al. 2006, Smith et al. 2012). Although many useful lessons have been learned from these types of studies – such as the advantages in using distributed models for ungauged locations - the conclusions regarding specific 'brands' of models are often not clear-cut. For example, the results are often influenced by the methodologies adopted (e.g. Reed 1984, Clarke 2008), the data intervals used (e.g. hourly), and whether data assimilation procedures were included in the evaluation.

As in most other areas of the flash flood warning process, performance monitoring and verification studies therefore provide the main routes to understanding whether a model adds value and identifying any improvements required. Also, it is worth noting that, rather than providing just a single configuration, some software developers now provide modelling toolkits which allow users to evaluate different types of stores, flow pathways, parameterization schemes, calibration criteria and other options.

Some examples of conceptual rainfall-runoff models used in operational real-time flood forecasting applications include those described by Burnash (1995), Lindstrom et al. (1997), Madsen (2000), Malone (1999), Moore (2007), Paquet and Garcon (2004), Quick (1995) and Zhao (1992). These include applications in Australia, Canada, China, France, the Netherlands, Sweden, the UK, and the USA. For data-driven models, examples include those described by Beven (2009), Dawson and Wilby (1999), Lees et al. (1994), Yang and Han (2006) and Young et al. (2012). Additional examples of both types are discussed in World Meteorological Organisation (2011). More general background on the techniques which are available is provided in the many books on hydrological modelling, such as those by Anderson and Bates (2001), Bedient et al. (2012), Beven (2012), Shuttleworth (2012) and Singh (1995).

Regarding physically-based models, their use in real-time flood forecasting applications is rare. However, physical-conceptual models have been increasingly adopted in recent years, particularly to provide flood alerts for ungauged catchments and/or longer range ensemble forecasts at a regional or national scale. Some operational examples include applications in Finland (Vehviläinen et al. 2005), France (Javelle et al. 2012; see Box 8.1), Europe (Thielen et al. 2009), the UK (Cole and Moore 2009) and the USA (see Box 5.1). The lead times and spatial scales considered vary widely but in some cases include flash floods. Models which focus mainly on overland flows are another option for arid regions (e.g. Yatheendradas et al. 2008).

However, in most cases, with these types of models the configurations are easily adapted to consider additional flow pathways, more frequent timesteps and smaller spatial scales as required; for example as higher resolution rainfall forecasts become available from meteorological services. In particular, models of this type are well-suited for use with the grid-based inputs provided by weather radar observations and nowcasting and Numerical Weather Prediction models. Compared to the

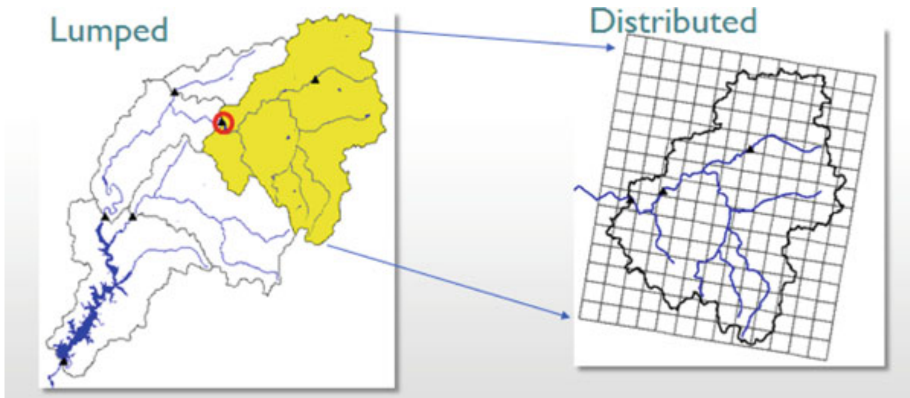

Fig. 5.4 Illustration of the difference between lumped and distributed modelling approaches for a sub-catchment (Cosgrove et al. 2010)

catchment-averaged or ‘lumped’ approach (e.g. Fig. 5.4), this detailed representation of spatial variations in rainfall is one of the key advantages of a grid-based approach, although is perhaps more demanding in terms of the quality of the precipitation inputs (e.g. Price et al. 2012).

In colder regions, the flows arising from snowmelt sometimes also need to be represented either as part of a rainfall-runoff model or as a separate modelling component. The causes of snowmelt typically include rising air temperatures, turbulent heat exchange, increased solar radiation, rainfall falling on snow, or a combination of these factors. Again, physically-based, conceptual and data-driven approaches have been developed, using lumped, semi-distributed and distributed configurations. For off-line studies, simpler empirical models based on cumulative energy inputs – estimated in terms of air temperature – are widely used, such as degree-day methods, and in some cases these allow for other factors such as wind speed and radiation (e.g. Hock 2003, World Meteorological Organisation 2009).

However, for real-time use, conceptual models are perhaps the most widely used approach. Typically these include one or more stores for the snowpack, with thresholds based on air temperature to define whether precipitation falls as snow or rain, and when snowmelt starts (e.g. Anderson 1968; Bell et al. 2000). Separate stores are sometimes included to take account of variations in elevation, snow cover, aspect and topography. Sub-models of this type are also widely included in physical-conceptual models and physically-based models (e.g. Koren et al. 1999; Dunn and Colohan 1999). As for rainfall-runoff modelling, the development of physically-based models is an active research area, and for snowmelt typically the aim is to represent the key mass, momentum and energy fluxes in the ground, snow layer and the lower atmosphere. Usually these approaches make extensive use of digital terrain models, land use datasets, satellite observations and meteorological observations and forecasts. As for rainfall-runoff models, the choice of modelling approach is not clear-cut and is best determined through model calibration and validation studies and the results from intercomparison studies, such as the international Snow Model Intercomparison Project (Essery et al. 2009).

Box 5.2 Distributed Hydrologic Model Flash Flood Application (DHM-TF)

The National Weather Service (NWS) in the USA has been developing and applying distributed hydrological models for more than a decade. Models of this type have the potential to maximise the benefits from using grid-based meteorological observations and forecasts and to provide estimates for flows at ungauged locations within a catchment. Parameter values can also be related to catchment characteristics, at least for the initial model set-up and calibration, before further fine-tuning of values. This work has been informed by the findings from two major distributed model intercomparison studies led by the NWS and involving participants from several countries (Reed et al. 2004; Smith et al. 2012).

As discussed in Box 8.2, distributed models are currently used operationally in the computation of Gridded Flash Flood Guidance. Also, for improved flash flood monitoring and forecasting, a new prototype system called DHM-TF (Reed et al. 2007; Cosgrove and Clark 2012) has been developed within an existing physical-conceptual modelling framework (RDHM, Koren et al. 2004). This can accommodate a wide range of runoff production and cell-to-cell flow routing approaches; for example using the SAC-HTET enhancement (Koren et al. 2010) of the Sacramento Soil Moisture Accounting model (SAC-SMA) in conjunction with a snowmelt model (SNOW-17) and a kinematic wave routing approach. The spatial and temporal resolution of the model can also be varied and is typically set to a grid length of 4 km with an hourly update interval.

To assess flash flood severity with the distributed model, the modelled flows are post-processed by DHM-TF using a threshold frequency approach to produce flood frequency estimates (Reed et al. 2007). This process evaluates the magnitude of the modelled flows against the gridded flow distributions derived using the same model over a long-term baseline simulation period, thereby helping to account for any inherent bias in the model outputs. Typically flooding is assumed to occur at a 1 in 2 year return period although a grid of locally derived values may be used if preferred, and are typically based on the outputs from regional or site-specific flood frequency analyses or engineering design studies (e.g. for culvert design). Within-bank estimates may also be appropriate as threshold triggers in some cases, such as for low water crossings. Typically a Log-Pearson Type III distribution is used in the calculation of the flood frequency estimates.

To maintain consistency with the real-time model, long-term baseline runs are performed using the same types of precipitation, air temperature and potential evaporation forcing inputs that are used in real-time. Where necessary, the archived values are adjusted beforehand to account for any changes in instrumentation or processing techniques which may have introduced bias and other inconsistencies into the data over time. Ideally at least 10 years of hindcast values should be used.

(continued)

Box 5.2 (continued)

The initial catchments selected for pre-operational testing were within the areas covered by the Baltimore/Washington, Pittsburgh and Binghamton Weather Forecast Offices (WFOs), covering domains with areas of 60,000, 89,000 and 57,500 km^2. The model can be configured to accept different types of precipitation inputs and the combination used in testing was:

- MPE – the Multi-Sensor Precipitation Estimator product combining weather radar, raingauge and satellite observations, with forecaster's inputs where necessary, and used for state updating of the model stores (4 km, hourly)
- HPE – the automatically generated High-Resolution Precipitation Estimator (HPE) product, which is based primarily on Nexrad observations, but adjusted based on recent MPE gauge/radar bias information (1 km, 15 min)
- HPN – short-range precipitation forecasts for 1–2 h ahead from the High-Resolution Precipitation Nowcaster product (1 km, 15 min)

The values in brackets show the spatial resolution of each product. Depending on the availability of information, the RDHM parameter values were based either on relationships derived using land-cover and geomorphological datasets, or locally available values already in operational use in other applications. Here, the initial parameter values were calibrated using US Geological Survey (USGS) streamflow information over the Binghamton WFO domain, but were used without calibration over the other evaluation domains.

For these studies, DHM-TF flood frequency values were derived using between 9 and 14 years of historical data. The approaches used for model validation included comparisons with evidence of flash flooding from observers (spotters), information on flash flood warnings issued by local Weather Forecast Offices, and comparisons with observed river flow data (where this was available). In some cases, it was necessary to exclude values which may have been affected by artificial influences such as reservoir operations.

Real-time tests on a number of events have shown that 'the model was able to accurately depict the timing and extent of flooding in both widespread tropical events and isolated convection-type events' (Cosgrove and Clark 2012). More generally, pre-operational testing has shown that visualisation of the outputs in flood-frequency terms provides a more useful indicator of flash flood potential than the estimated flow values themselves (e.g. Fig. 5.5).

The model can also be operated with or without flow routing enabled between cells, with a routing approach generally providing better results for widespread events and/or on main rivers with large channels whose catchments

(continued)

Box 5.2 (continued)

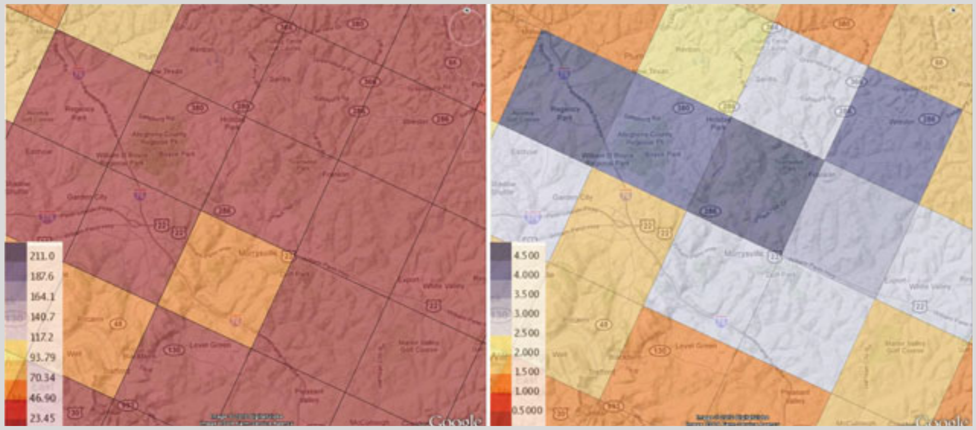

Fig. 5.5 Example of peak discharge estimates (*left*) and flow return period estimates (*right*) for the 4 km grid DHM-TF model (Cosgrove et al. 2010, Google™ and Digital Globe™)

cover several grid squares. By contrast, the non-routing approach generally performs better for smaller creeks and streams which fall mainly within individual cells, particularly for localised rainfall events. For example, Fig. 5.6 shows an overview of the model outputs for a flash flood event in Virginia on 7 August 2011 which led to several rescues and many road closures. The storm was concentrated around the city of Culpepper but flooding also occurred in Falmouth further downstream, which received considerably less rainfall, but for which the cell-to-cell approach provided an excellent indication of both the severity and timing of the flood which occurred.

Compared to existing flash flood guidance approaches (see Box 8.2), some key advantages of this distributed approach include (Cosgrove and Clark 2012):

- Quantitative estimates for the likely severity of flooding (not just binary occurrences)
- More flexibility in the grid scales used, with the option for flow routing between grid cells
- The option to include a snowmelt model, where appropriate
- The potential for more frequent updating of outputs

Current planned development work includes evaluating the approach for further locations, reducing the time delay (latency) between observations and forecasts, assimilation of satellite-based snow and soil moisture observations, use of higher spatial and temporal resolutions, and evaluation with new precipitation products, as these become available. For example, Fig. 5.7 illustrates the much greater detail provided by moving from a 4 km to a 1 km

(continued)

Box 5.2 (continued)

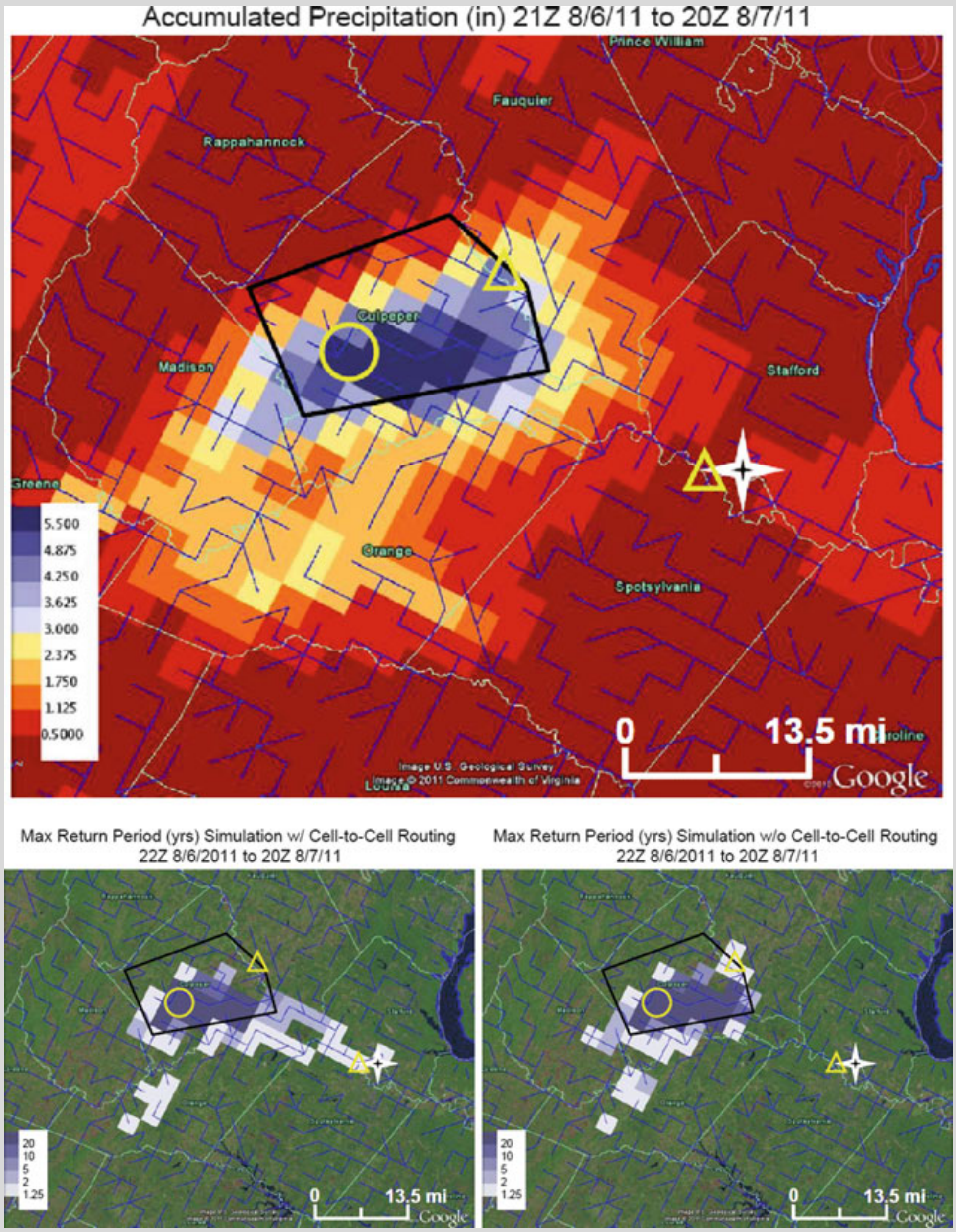

Fig. 5.6 Illustration of the precipitation and model outputs for a flash flood event in Virginia on 7 August 2011 showing the accumulated precipitation during the flood period (*top*) and the maximum return period during the event as simulated by DHM-TF with (*lower left*) and without (*lower right*) cell-to-cell routing. The *black border* depicts the Weather Forecast Office flash flood warning which was issued, *yellow triangles* indicate US Geological Survey stream gauges, the *yellow circle* depicts the location of local storm reports of flash flooding, and the *white star* indicates the location of rescued swimmers (Cosgrove and Clark 2012, Google™ and Europa Technologies)

(continued)

Box 5.2 (continued)

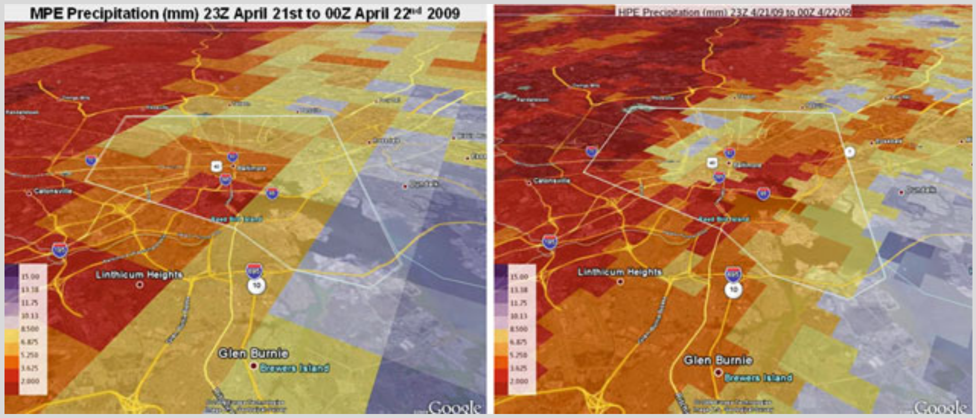

Fig. 5.7 Illustration of 4 km MPE and 1 km HPE inputs for a flash flood event in April 2009 in Baltimore, Maryland (city boundaries shown by the white outline) (Cosgrove et al. 2010, Google™ and Europa Technologies)

grid scale for a pilot study for the city of Baltimore. To improve situational awareness, new ways are also being explored into providing forecasters with real-time feedback on current flash flooding incidents from emergency managers and other groups, such as the use of chat rooms and social media.

5.2.2 Flow Routing Models

Flow routing models are typically used to represent the translation of flows from upstream locations in a catchment to sites further downstream. The main approaches include:

- Hydrological routing models – which typically conserve the water balance in a river reach, using approximations to the full equations of motion or more empirical formulations. Examples include the kinematic wave and Muskingum-Cunge approaches (Lighthill and Whitham 1955; Cunge 1969)
- Hydrodynamic models – which solve 1-, 2- or 3-dimensional approximations to the Navier Stokes equations of motion; for river modelling applications, the depth-averaged shallow water Saint Venant equations are widely used (e.g. Chow 1959; Chanson 2004; Ji 2008)

Models of this type are also used in some other applications. For example, the kinematic wave approach is widely used to route flows between grid cells in distributed rainfall-runoff models, and hydrodynamic models are increasingly used for surface water flow modelling in urban areas (see Chap. 10) and in dam break risk assessments (see Chap. 11).

For a simple river reach with no complications, the main effects which need to be captured typically include the time delay and attenuation of the flood wave as it passes down the channel, and any significant inflows or outflows (e.g. from tributaries or abstractions). Hydrological flow routing models often provide reasonable results for this type of situation and are both simpler to calibrate and faster to run than hydrodynamic models. Also river channel and floodplain survey is usually not required, although some commercially available packages provide the option to estimate key parameters such as wavespeed and attenuation coefficients using indicative channel cross sections. Another approach which is sometimes used is to apply peak-to-peak level or flow correlations over the full range of flows, rather than just for peak values; however, this makes no allowance for attenuation and other influences and is a purely empirical approach.

By contrast, hydrodynamic models are usually considerably more time consuming to build and calibrate, but better able to represent factors such as tidal influences, operations at flow control structures, and floodplain flows. Whereas a typical node spacing for a hydrological approach is of the order 1 km or more, grid lengths are usually much less than this in a hydrodynamic model and perhaps just a few tens of metres or less in areas of interest, particularly in urban surface water models. Key structures which exert an influence on flows can also be included, such as bridges, weirs and culverts, using dimensions based on design drawings and/or survey data. Normally, unless suitable results are available from a previous study, a river channel survey needs to be commissioned, typically using depth or echo sounders from a boat, with traditional survey for any floodplain areas. Alternatively, digital elevation models are widely used for the floodplain component; for example based on high resolution Light Detection and Ranging (LiDAR) survey by aircraft or helicopter.

The main parameters which need to be defined during model calibration typically include the loss coefficients at key structures and the river bed and floodplain. For flood inundation modelling (Pender and Néelz 2011), one approach to the classification of models is as follows, where the numbers in brackets represent the dimensions of the model:

- Solution of the one dimensional St. Venant equation (1D)
- 1D plus a storage cell approach to the simulation of floodplain flow (1D+)
- 2D minus the law of conservation of momentum for the floodplain flow (2D-)
- Solution of the two-dimensional shallow water equations (2D)
- 2D plus a solution for vertical velocities using continuity only (2D+)
- Solution of the three-dimensional Reynolds averaged Navier-Stokes equations (3D)

These approaches represent river channel and floodplain flows in increasing amounts of detail, and a common choice for flood risk mapping is a combined 1D/2D approach for the river channel and floodplain. However, although it is difficult to generalize, the model run times required often increase as the model complexity increases so, for that reason, most real-time applications use 1D or 1D+ approaches. However, two dimensional approaches are starting to be used for the surface water component in urban flood forecasting applications (see Chap. 10) and computer processor and algorithm improvements are increasingly making this approach feasible for river forecasting applications.

Despite these advances, models developed for off-line (simulation) studies are sometimes still too slow for real-time use, and some widely used techniques for reducing run-times include removing unnecessary detail and improving the stability and convergence of the model (e.g. Chen et al. 2005; Werner et al. 2009). In many cases it is possible to reduce run-times to the order of minutes or less, depending on the number of nodes, computer processors used, run duration etc. However, to avoid the risk of a model run failing to complete, it is important that models are stable in real-time use and tested over a wide range of flows during calibration, including synthetic events higher than those observed to date. Other aspects of the model may also need to be improved, such as including the current condition of structures (e.g. embankment heights) and replacing the runoff components with models more appropriate for real-time use. Reducing bottlenecks in data transfer provides another possible way to significantly reduce overall run times.

For flash flood applications, these types of models are perhaps less widely used than for slower responding lowland rivers; in part because of limitations on the amount of real-time river gauge data available. However, as discussed in the previous section, there are often advantages in linking a number of rainfall-runoff models together using flow routing reaches to form an integrated catchment model. This then provides some representation of the influence on flows of the spatial variations in rainfall. Also, this allows forecasts to be updated at any intermediate gauges in the catchment before being routed through the network, thereby maximizing the benefits from all of the observations which are available. As discussed in Chap. 8, it is also possible to represent operations at reservoirs and flow control structures to varying degrees, such as by including logical rules to represent the control procedures which are used operationally.

Another possibility with hydraulic models is to produce real-time inundation maps and this approach has been used for both river and surface water flooding applications. However, one key consideration is the increase in run-time associated with the additional complexity although, as noted earlier, computing speeds continue to improve. Also, in recent years, faster running options – such as rapid floodplain spreading models – have become available commercially which run much more quickly than the underlying models from which they are derived, with little reduction in accuracy.

However, another potential issue is that – under the pressure of a flood event – there is often little time to check the model outputs whereas, for off-line flood risk mapping studies, there is usually the opportunity for an extensive consultation exercise regarding the draft maps before they are finalized. As a result, real-time inundation mapping tends to be used only in situations where errors are not critical and/or the model outputs have been extensively validated against past flood inundation outlines for a number of calibration events. Instead, the more usual approach is to develop GIS-based viewers, map books and decision support systems which allow users to relate forecast outputs (e.g. levels at gauges) to likely flood extents based on pre-defined maps. Box 1.1 provides an example of this approach and

Chap. 8 includes some further discussion of this point. However, for the future, as model run-times reduce and data assimilation techniques improve, real-time applications are likely to become more commonplace.

5.2.3 Data Assimilation

Another key distinguishing feature between types of models is the approach used for data assimilation. As discussed earlier, these techniques make use of real-time observations to attempt to improve the model outputs. Some alternative names include real-time updating or adaptation.

Errors in model outputs typically arise from a number of sources, such as adoption of an inappropriate model structure and uncertainties in the model parameters, boundary conditions and initial conditions (e.g. Beven 2009). Event-specific factors such as debris blockages, ice jams and defence breaches may also lead to conditions occurring which were not considered in the original model development. A distinction is sometimes also made between initialisation, modelling and forcing errors, where the forcing component arises from any forecast inputs beyond the present time; for example, from rainfall forecasts, or flow forecasts from model components further upstream in an integrated catchment model. These in turn introduce additional sources of uncertainty into the model outputs.

The main approaches which are used for data assimilation include (e.g. Serban and Askew 1991):

- Input updating – adjustment of the inputs to the model
- State updating – adjustment of the initial model states
- Parameter updating – adjustment of the parameters of the model
- Output updating – adjustment of the outputs from the model

Table 5.2 shows some examples in each category and Fig. 5.9 (see later) illustrates how each approach fits within an overall flood forecasting system.

Output updating can be performed independently from the model and therefore applied to any approach. By contrast, state and parameter updating methods require the facility to change the internal stores or parameters of the model programmatically (or manually) between successive model runs. Typically this is a feature of the software package used and this is sometimes also the case for input updating.

Of these methods, state and output updating techniques are perhaps the most widely used and this is due in part to concerns about the validity of the other approaches in some situations. For example, it is normally better to resolve problems with input data (e.g. rating curves) as part of the processing of observations, rather than to attempt to do this via data assimilation. However, inflow adjustments are sometimes used in hydrodynamic models, repeating model runs within the same forecast cycle. Regarding parameter updating, for physically-based models and most conceptual models the parameters are generally held to have some physical meaning, so again should perhaps not be adjusted as part of an updating procedure.

Table 5.2 Some examples of data assimilation techniques used in real-time flood forecasting applications (see Chap. 12 for references to several of these techniques)

Type	Model	Examples
Input	Hydrodynamic	Distribution of errors into tributary inflows or the use of pseudo-inflows
State	General	Kalman filtering (including extended and ensemble versions)
	Conceptual rainfall-runoff	Adjusting store contents
	Physical-conceptual rainfall-runoff	Variational and Kalman filter techniques
	Hydrodynamic	Ensemble Kalman filter
Parameter	Transfer function	Adjustment of model parameters
	Hydrodynamic	Adjustment of roughness coefficients
Output	General	Error prediction methods, adaptive gain

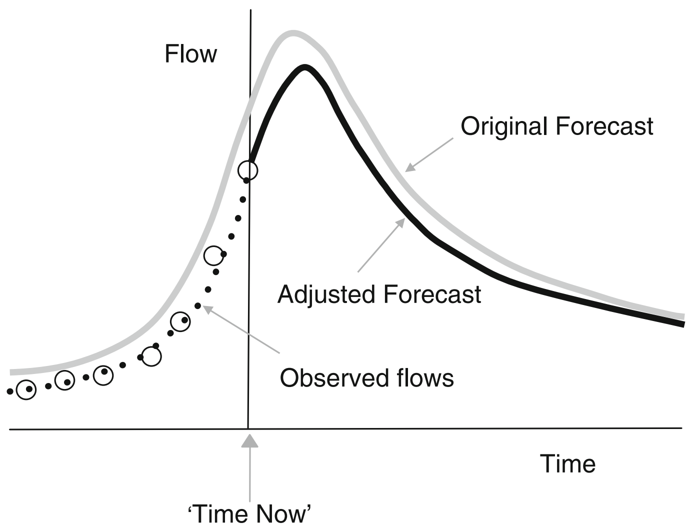

Fig. 5.8 Example of an error prediction approach to data assimilation

However, where the parameters are known to typically fall within a range then adjustments within that range are perhaps more valid to make; for example for the roughness coefficient in a hydrodynamic model. Parameter updating is also a widely used option for data-driven models.

Figure 5.8 illustrates the principles of updating for the case of an error prediction routine. In this approach, the differences between observations and forecasts are analysed over a number of flood events, and a time series model is fitted to these residual errors; for example using an Autoregressive Moving Average (ARMA) approach. Success then relies on there being some statistical relationship between successive values, such as consistent over- or under-prediction, which is often the case. In real-time operation, the time series model is then used to derive adjustments to the forecast. As illustrated in the figure, these often reduce with increasing lead time as the influence of the observed values decays. The adjusted forecast then converges towards the original estimate beyond times which are comparable to the response time of the catchment (for a rainfall-runoff model) or the time delay in a river reach (for a flow routing model). This is a general characteristic (and constraint) in many other approaches to data assimilation with the result that, at longer lead times, the model is in effect operating in simulation mode.

More generally numerous studies have suggested that data assimilation improves forecast accuracy provided that the data quality is good enough to support the chosen approach. However, normally when time permits it is good practice to compare the adjusted and unadjusted forecasts before approving a forecast for issue since data assimilation sometimes degrades a forecast. For example, this can occur due to erroneous high flow ratings, or when the algorithm is focussed on one type of correction when the underlying problem is of another type; for example, some error prediction methods struggle to distinguish between magnitude and timing errors under high flow conditions. Again, such issues can to some extent be resolved as part of the model calibration and validation process.

Nowadays, most adjustments are performed automatically although manual 'blending' techniques are still sometimes used, in which the forecaster adjusts values visually, typically with the assistance of an interactive graphical user interface. However, there is often insufficient time for a manual approach in flash flood situations, and sometimes for comparing original and updated outputs. When an automated approach is used, usually this needs to be calibrated and validated off-line, although some self-calibrating methods are available. Ideally, the approach used operationally would be optimized for the forecast lead times and performance measures of interest, as discussed further in Section 5.3. Some more general discussions of the relative advantages and disadvantages of different techniques include the intercomparison studies reported by O'Connell and Clark (1981), Refsgaard (1997) and Goswami et al. (2005) and the reviews by Serban and Askew (1991), Moore (1999) and World Meteorological Organisation (2009).

For distributed models – both hydrological and hydraulic – an additional challenge is to adjust conditions over the full domain of the model, based on river gauge (or other) observations at just a few point locations. This is similar to the data assimilation problem in Numerical Weather Prediction models (see Chap. 4) and some methods which have been used include variational and ensemble Kalman filter techniques (e.g. Lee et al. 2012 and Box 8.3). More generally, the use of distributed observations from satellites, sensor networks and other sources is an active area for research and this topic is discussed further in Chap. 12 together with probabilistic data assimilation techniques, which use real-time data to both reduce and quantify the uncertainty in forecasts.

5.2.4 Probabilistic Flood Forecasting

As discussed in Chap. 1, in recent years, probabilistic and ensemble forecasting techniques have started to be used more widely in operational flood forecasting.

This potentially leads to better decision-making during flood events and helps to guide longer-term improvements in models and observation networks. For example, Beven (2012) notes that in real-time operational forecasting "….allowing for uncertainty means being right more often in terms of bracketing when warning thresholds are crossed. It also gives a more realistic representation of forecasting capability in communicating with professional partners…."

The first operational applications of these techniques date back 20 years or more (e.g. Beven 2009; Day 1985; Krzysztofowicz 2001). However, development has been accelerated by the almost universal adoption since the 1990s of ensemble forecasting techniques in Numerical Weather Prediction (see Chap. 4) This has led to the implementation of an increasing number of ensemble flood forecasting systems worldwide (e.g. Cloke and Pappenberger 2009). For example the European Flood Alert System (EFAS) was one earlier adopter of this approach, and provides 3–10 day ahead ensemble forecasts to local water authorities in transnational river basins across much of Europe (Thielen et al. 2009).

The international Hydrological Ensemble Prediction Experiment initiative (HEPEX) has also been instrumental in identifying research needs and encouraging case studies (test beds) in this area (e.g. Schaake et al. 2007). The impacts of other sources of uncertainty are also increasingly considered, such as from observation errors and uncertainties in model parameters. These effects are generally more apparent at shorter lead times than when using ensemble rainfall forecasts and can be accounted for individually or – more usually – by estimating the overall predictive uncertainty based on observations and current forecasts. The increasing availability of ensemble radar outputs and probabilistic nowcasts has also increased interest in using these types of products as inputs to flash flood forecasting systems.

These are all active areas for research and Chap. 12 introduces some of the approaches which are used including forward uncertainty propagation, probabilistic data assimilation and probabilistic forecast calibration techniques. Another key consideration is how to present and interpret the resulting ensemble or probabilistic outputs. At the simplest level, these are used as a visual guide to the confidence to attach to forecasts, typically using formats such as 'spaghetti diagrams' and plumes. Several examples are shown in later chapters for flash flood applications, such as in Boxes 8.3 and 12.3.

However, another approach is to use the outputs more formally as part of the decision-making process when issuing flood warnings. Some examples of the techniques which are used (or under evaluation) include probabilistic flood warning thresholds, cost-loss approaches, and methods which consider the relative economic value of forecasts to end users. There is also the potential to use a more risk-based approach to issuing flood warnings, based on the probability and consequences of flooding. Again these are all developing areas and Chap. 12 considers some of these approaches further, including the issue of how best to convey the uncertainty in flood forecasts to end users.

5.3 Operational Considerations

5.3.1 Forecast Interpretation

As a flash flood develops, flood forecasting and warning duty staff generally make use of information from a number of sources to evaluate the potential for flooding. Table 5.3 shows some examples of the sources which are potentially available.

In most organisations, the decision to issue a warning usually involves some expert input and, due to the risks of false alarms and missed warnings, completely automated approaches based on forecasts alone are only used occasionally, although automated approaches based on observations are more widespread; see Chaps. 6–12. However, where confidence in a model is high, the use of forecast

Table 5.3 Some examples of the types of information which are potentially available to forecasting and warning staff when deciding whether to issue flood warnings

Item	Description
Decision support tools	Map-based computer systems to display on-the-ground information from telemetry and observers together with rainfall and flood forecasts; see Chap. 6.
Forecasting models	Both deterministic and ensemble forecasts (if available) and the outputs from simpler models (if available), in some cases also displaying the outputs from recent model runs for comparison
Forecast discussions	Discussions with colleagues and others involved in the flood warning and emergency response process regarding their views on how the situation will develop; for example, operational staff, meteorologists, civil protection staff, and emergency responders
Local knowledge	Experience of the types of conditions which lead to extreme weather and flooding in a catchment, taking account of topography and other factors, and of model performance in those conditions. Also a knowledge of potential locations with a significant risk from flash flooding
Observations	Recent river, rainfall and other observations and – if relevant – reports from staff on site such as flood patrols and volunteer ‘spotters’, plus information from the public and others by phone, social media and other sources
Risk tolerance	Attitudes to risk both at an organizational level and in specific communities based on lessons learned from previous flood events, particularly regarding missed warnings, late warnings, false alarms, near misses, and the frequency at which alerts and warnings should be issued in advance of flooding
User requirements	The lead times and message formats ideally required by emergency responders, civil protection authorities, communities and others, particularly for warnings likely to lead to evacuation of properties and impacts on critical infrastructure, in some cases considering factors such as the time of day (or night) and meteorological conditions (e.g. air temperature, ‘wind-chill’). Also the need to provide a consistent message when possible, even if forecast outputs are varying widely between model runs

thresholds is often formally included in warning procedures, as illustrated in Chaps 6 and 8 for the case of river flooding.

This general approach is similar to that used by meteorological forecasters and discussed in Chap. 4. However, the way in which forecast information is used depends to some extent on the approach used for issuing flood warnings. For example, in some organisations the forecasting and warning roles are separated, with forecasting performed at a national or regional level and the decisions to issue warnings made at a local level. In this case, forecasters provide advice to colleagues (not necessarily in the same organization) who then decide whether to issue a warning. Chaps. 1, 6 and 7 discuss this topic further.

During a flood event, it is also often useful to perform additional forecasting model runs to investigate possible scenarios, and to repeat analyses if suspect observations are identified. Table 5.4 shows several examples of the types of tasks which are sometimes required. Note that the need to switch to more frequent forecasting runs varies between organisations; for example, in some systems, telemetry observations are received year-round at the same reporting interval (e.g. 15 min) whilst, in others, less frequent polling is used in periods with no significant flood threat, with written procedures for switching from one state to the other. As discussed in Chap. 3, normally the latter approach is used to reduce telemetry costs and/or power consumption at gauging sites. In some organisations, forecasting and warning staff also contribute to wider aspects of the emergency response but again the extent to which this occurs depends on organisational structures.

5.3.2 Forecast Verification

As part of the development of a flood warning service, another key task is to review model performance, improve existing models, and develop new models. Models may also require recalibrating to account for external factors such as changes in rating curves by hydrometry teams and construction work in the catchment (e.g. new flood defences). Forecast verification provides a key tool for understanding how models perform and identifying areas for improvement (e.g. Demargne et al. 2009) and is normally performed at regular intervals and following major flood events. In some organisations there is also a requirement to report on specific measures as part of service level and other agreements. Alternative names which are used include performance measurement, performance monitoring and post-flood analysis.

The measures which are used are similar to those for rainfall forecast verification and discussed in Chap. 4. Typically some key parameters of interest include:

- Hydrograph-characteristics – indicators of how successful the model was at predicting peak levels, the timing of the peak, and the overall shape of the hydrograph. Some measures used include the bias, R^2 efficiency, root mean square error, and peak magnitude and timing errors
- Threshold crossing measures – indicators of the performance of the model in forecasting the crossing of key flood warning and flooding thresholds. When

Table 5.4 Some examples of flood forecasting related tasks which may be required during flash flood events

Item	Description
Forecast adjustments	In some hydrological services, interactive computer-based tools are provided to adjust forecasts for any significant bias or other problems and for manually blending observations and forecasts. In some cases, forecast runs are repeated from revised initial conditions if any obvious problems are noted with the observations or other inputs to the model (e.g. rainfall forecasts)
Forecast advice	Another key role is often to provide expert advice to colleagues, external partners (civil protection, emergency response etc.) and possibly the public on how to interpret forecasts in terms of flooding impacts, and on confidence in the values provided, based on past experience and ensemble outputs (where these are available). This sometimes includes writing forecast commentaries and discussions to include in flood warning messages (for example, on publicly accessible websites) and taking part in phone- and web-based conference calls
Forecast approval	Often forecasts need to be formally approved before release for use in the flood warning process; typically this is done by selecting an option in the forecasting system which automatically changes the status of the forecast
Scenarios	Running 'what-if' scenarios as required to investigate the risks from event-specific flooding issues if they seem likely to develop, such as for a potential levee breach, dam break or ice jam, and more generally to explore possible alternative operational options and meteorological outcomes (e.g. What if this storm turns out to be a repeat of the January 1991 event? What if the rainfall stops now? What if we draw down this reservoir by another two metres?). This sometimes includes running off-line 1- or 2-dimensional flood inundation mapping models on demand; for example for dam break scenarios
Thresholds	Monitoring river levels, reservoir levels, rainfall amounts and forecasts against pre-defined thresholds and alerting others when key decision criteria are met or thresholds passed, and/or initiating more frequent polling of river and raingauge telemetry data and forecasting model runs. Normally the initial alarm handling is performed automatically by the telemetry or forecasting system; the forecaster's role is then to decide if the observations or forecasts are credible and the actions to take; for example by following established flood warning procedures (see Chaps. 6 and 8)

evaluating performance across a number of events, some typical measures used include the Probability of Detection, False Alarm Ratio and the range or mean value of timing errors

Values are typically evaluated at a range of lead times to help to identify the maximum lead times at which the model provides operationally useful information; for example, using R^2 values for the 15 minute, 1-, 2-, 3-, and 6-hour ahead forecasts. Most forecasting systems provide automated tools to assist with reporting on performance statistics such as these. Of course, it is also useful to evaluate the model

Table 5.5 Example of a 2 × 2 contingency table, relating to the number of observed and forecast instances of crossing a flood warning threshold

	Threshold crossed (observed)	Threshold not crossed (observed)
Threshold crossed (forecast)	A	B
Threshold not crossed (forecast)	C	D

performance in terms of its simulation (off-line) performance, without data assimilation.

Some general discussions of the merits of the various techniques which are available include the comprehensive reviews – in a meteorological context – by Stanski et al. (1989) and Jolliffe and Stephenson (2011). However, as in meteorology, different measures are sometimes relevant to different applications; for example, for levee floodfighting operations, issuing flood warnings and reservoir operations, the aspects of the forecast most of interest might include peak values, the threshold crossing performance, and the flow volume for the event respectively.

Therefore, typically a range of measures is chosen to highlight different aspects of the model performance and in some cases these may show areas of contradiction. For example, a model might be very successful at forecasting the overall shape and magnitude of the hydrograph at a range of lead times but consistently show a timing error in peak values and at critical flood warning threshold levels. Normalised values are sometimes also useful to allow comparisons to be made between different catchments, periods and models. Ideally it should also be possible to quantify the improvements from forecaster interventions although as yet this topic is rarely considered in hydrological forecasting (e.g. Pagano 2012).

As discussed in Chap. 4 threshold-based measures are normally evaluated using a contingency table approach. Table 5.5 shows an example of a simple 2 by 2 (2 × 2) table based on a single threshold value; if required, more complex tables can be used considering a range of threshold values and outcomes. In this example, the Probability of Detection (POD) is given by A/(A + C) and the False Alarm Ratio (FAR) by B/(A + B) (and is often called the False Alarm Rate in hydrological studies). Many other measures can be derived even from this simple table, of which the Critical Success Index (CSI) is perhaps the most widely used, and is equal to A/(A + B + C).

As in meteorological studies, measures are typically evaluated over long periods and/or a number of events. Again, this requires access to or generation of an archive of previous observations and forecasts and again ideally both the model configuration and observations would reflect the current operational status; for example, taking account of any changes in raingauge locations, datum levels, rating curves and other factors over the time period covered by the verification exercise.

For flood forecasting models, this hindcasting or reforecasting task is generally simpler and faster to perform than for the meteorological equivalent. Indeed, if observations and forecasts are routinely archived, and there have been no significant changes in a period, it may be legitimate to perform a verification exercise based solely on this operational dataset. However, if nowcasts or Numerical Prediction

Model outputs are used as model inputs, then the reforecasting process for those components can be a considerable undertaking (see Chap. 4).

In some cases, exploratory modelling studies are useful to provide insights into different aspects of the model performance. Typically these tests are performed in an off-line version of the operational forecasting system, with data assimilation both enabled and switched off (to assess its impact) and with verification measures calculated for a range of lead times. For example, for fast response catchments, it is often useful to compare performance measures for a range of lead times for different rainfall scenarios, such as the following examples:

- Observations only – for each event, the use of observed values up to the time of the forecast, and then null or zero values
- Perfect foresight – use of the actual observations from each event as a pseudo rainfall forecast
- Rainfall forecasts – use of the forecasts from each event, combined with observed values up to the time of the forecast ('time-now')

Sensitivity tests such as these then highlight issues such as the potential for rainfall forecasts to extend lead times, the likely performance using the ideal of a 'perfect' forecast, and the actual operational performance, based on current rainfall forecasting techniques. Additional scenarios, such as failures at individual river and raingauges, might also be considered.

Another general issue is how to verify forecasts made using distributed models, and more approximate methods such as rainfall depth-duration thresholds and Flash Flood Guidance techniques (see Chap. 8). This is particularly the case for ungauged catchments and one approach which is increasingly used is to make use of manual observations; for example those made by volunteer 'spotters' and/or based on calls or interviews with residents and businesses to determine the number of successful warnings and false alarms. This topic is discussed further in Chaps. 6 and 7 and Box 5.2 illustrates an application of this approach.

With the increasing use of ensemble flood forecasts, as in meteorological forecasting a need has arisen to develop suitable verification measures for these types of outputs. Again, a hindcasting exercise allows key aspects of the probabilistic content of forecasts to be compared with the observed record; for example, in terms of probability density functions and the probabilities of crossing flood warning thresholds. As mentioned in Chap. 4, some desirable aspects of probabilistic flood forecasts include (e.g. Weerts et al. 2012):

- Reliability – a measure of the agreement between the forecast probability and the observed frequency over many flood events (e.g. the forecast bias)
- Resolution – an indication of the ability of the forecast to discriminate between true events and true non-events among different events
- Sharpness – a measure of the tendency to forecast with a concentration of large probabilities around some value, as opposed to small probabilities spread over a wide range of values

Some measures which are widely used include the Relative Operating Characteristic, Continuous Ranked Probability Score and Brier skill score (e.g. Laio and Tamea 2007, Casati et al. 2008, Pappenberger et al. 2008, Bartholmes et al. 2009). Another recent development has been to consider verification measures for real-time use to assist with operational decision-making, such as identifying archived forecasts analogous to the current situation with the associated verification statistics (Demargne et al. 2009).

However, these technical aspects are of course just one measure of the value of a forecast to the end user. For example, Chap. 6 discusses some of the measures used to assess the overall performance of flood warning systems. Typically these depend on a range of social, procedural and other factors, as well as the purely technical issues relating to forecast model performance.

5.3.3 Forecasting Systems

Where budgets and resources allow, flood forecasting models are normally operated within a flood forecasting system (e.g. Fig. 5.9). Some advantages of adopting this approach typically include the automation of routine tasks, maintaining audit trails during a flood event, and producing a wider range of outputs than would otherwise be possible. These factors also help to free up the time available to forecasters for other tasks of the types discussed in Sect. 5.3.1, such as the interpretation of model outputs and performing 'what-if' scenarios.

Typically a forecasting system manages the processes of data gathering, initial data validation, scheduling of model runs, and post-processing of model outputs. As discussed in Chap. 3, some systems also include a telemetry polling component with alarm handling and flood warning dissemination components. The number of inputs required can be large, and could include river, reservoir, lake and tidal levels, control structure settings, raingauge, weather station and weather radar observations, and meteorological forecasts of various types.

As for all other components in the flood warning process, forecasting systems need to be resilient to problems and failures, both within the system and from external factors. Some examples could include a telemetry gauge failing, a hydrodynamic model run failing to complete, and power and communications failures. Some approaches to helping to increase resilience include the use of backup power supplies, and operating duplicate versions of key systems such as computers and telemetry links.

For example in some cases the backup system is installed at some distance from the main centre in case of widespread flooding or power cuts, earthquakes, or other region-wide hazards. As noted in Chaps. 3, 6 and 7, some organisations maintain a back-up operations centre, with regular tests of procedures for transferring control from one location to another. Data hierarchies are also widely used; for example, if the weather radar input fails, use raingauge observations, and if that is not possible use a stored rainfall profile. Similarly, backups are often used for models, such as operating a hydrological flow routing model or correlation as a backup for a hydrodynamic model.

In case of the complete failure of all electronic equipment, simple paper-based forecasting procedures are normally kept as a backup, such as lookup tables or

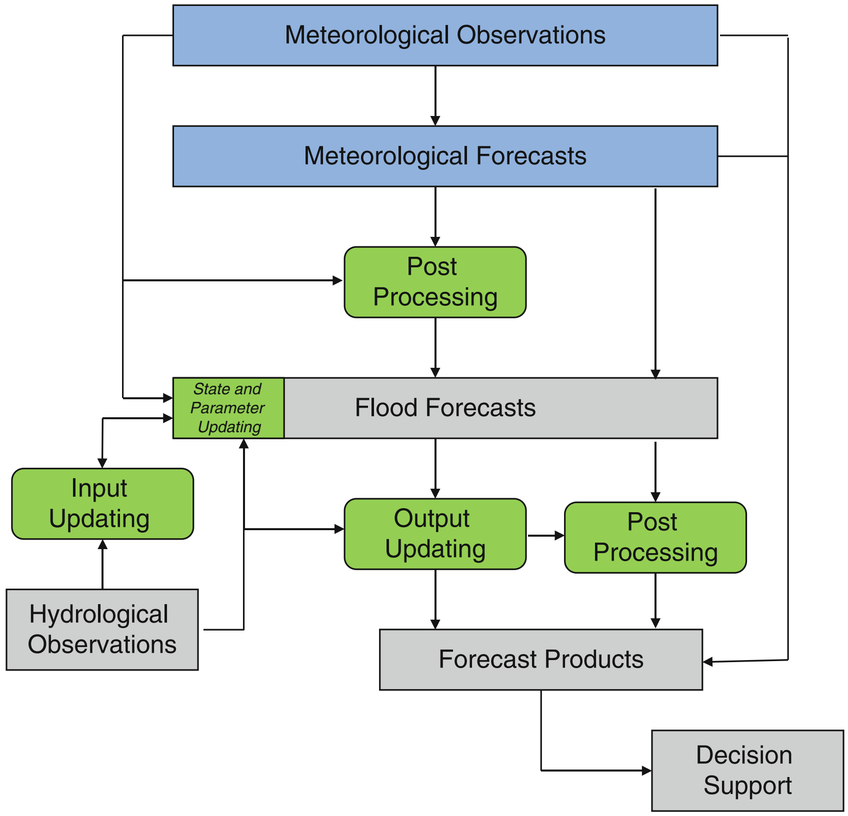

Fig. 5.9 Illustration of some possible linkages between meteorological and flood forecasting systems. Note that not all components and links are always used or required. Also, usually only one form of data assimilation would be used. Similar diagrams have also been produced by World Meteorological Organisation (1992) and Refsgaard (1997), amongst others

graphs, with observed values relayed by hand-held radios or other means. Further possible points of failure may become apparent from a systematic review, performed as part of contingency or business continuity plans. For example, as discussed in Chaps. 2, 3 and 6 river gauges are often made more resilient by raising key equipment above possible flood levels or moving instruments to safer locations, and multiple routes are used for disseminating flood warnings.

Table 5.6 illustrates some of the functionality which is typically available in modern flood forecasting systems. Many flood forecasting centres operate systems of this type, either developed 'in-house' or using commercially available products. Some examples include the operational systems in Finland (Vehviläinen et al. 2005), and the UK (Werner et al. 2009) and several other examples are briefly discussed in other chapters, such as in Boxes 1.1 and 8.3. Normally a user-friendly map-based interface is provided, with the options to view and compare forecasts using graphical, tabulated and other types of output. Model configuration, calibration and validation tools are sometimes included, and open-architecture systems are increasingly used, which are open in the sense that any model which meets certain standards can be included in the system.

Table 5.6 Some typical functionality in flood forecasting systems (adapted from Sene 2010)

Item	Function	Description
Pre-processing	Data gathering	Polling of instruments directly, or receiving data from a separate telemetry system (see data interfacing)
	Data interfacing	Interfacing to a range of real time data feeds and forecast products from various sources (meteorological, river, coastal), possibly also including grid-based or catchment averaged weather radar data and meteorological forecasts, and possibly ensemble inputs (e.g. rainfall forecasts)
	Data validation	Real time validation using a range of time series, statistical, spatial and other validation methods
	Data transformation	Transformation of input data into the values required by the modelling system (e.g. catchment rainfall estimates), including infilling missing values by interpolation, regression and other methods
Model runs	Model run control	Scheduling and control of model runs, including ensemble forecast runs, model initialization, error handling, and operation of simpler back-up forecasting models (if available), including automatically initiating model runs over longer periods if there has been a gap in operations
	Data assimilation	Application of real time updating and data assimilation algorithms, with comparisons of original and updated forecasts, and possibly allowing forecasters to manually adjust forecasts
	Data hierarchy	Automatic fall-back to alternative options in case of failure of one or more inputs
Post-processing	Model outputs	Processing of model outputs into reports, maps, graphs, web-pages etc. and for onward transmission to decision support systems and end users (as required)
	Inundation mapping	Intersection of inundation extents with street and property databases to generate maps and lists of properties at risk
	Alarm handling	Raising alarms when thresholds are forecast to be exceeded, using map based displays, email, text messaging etc.
	Data storage	Maintaining an archive of all input data, forecasting model run outputs and other key information
	Performance monitoring	Automated calculation and reporting of information on model performance and system availability
	Audit trail	Maintenance of a record of data inputs, model run control settings, model forecast outputs, operator identities etc.
	Replay	The facility to replay model runs for post event analysis, operator training and emergency response exercises

(continued)

Table 5.6 (continued)

Item	Function	Description
User interface	General	Map based, graphical and other displays of input data, forecast outputs, alarms etc., including overlays of aerial and satellite photography
	What-if functionality	The option to run scenarios for future rainfall, flood defence breaches, gate operations, dam breaks etc.
	System configuration	Interactive tools for off-line configuration of models, data inputs, output settings, alarms etc, and to define user permissions and passwords (e.g. view, edit, administrator)
	Model calibration	Off-line tools for calibration of models

5.4 Summary

- Flood forecasting models are widely used as part of the flash flood warning process. The main application is usually to provide information which helps warnings to be issued earlier than is possible from observations alone and assists with interpreting complex situations. The potential gain in warning lead time is particularly useful for flash flood applications
- The choice of modelling approach typically depends on a wide range of factors including catchment response times, required warning lead times, data availability, institutional capacity, budgets and the level of flood risk. Risk-based approaches are widely used to prioritise model developments and, in some cases, investments need to be justified using a cost-benefit or multi-criteria analysis
- Simple techniques such as correlations, rate-of-rise approaches and time of travel methods are still widely used operationally, particularly in community-based flood warning systems. They also provide a useful backup for more sophisticated approaches. However, the latest forecasting models typically combine rainfall-runoff and flow routing components using an integrated catchment model or distributed modelling approach
- Rainfall-runoff models are used to estimate flows from observed and forecast rainfall. The main types are conceptual, data-driven and physically-based models plus various hybrid approaches. Conceptual and data-driven models are typically operated on a lumped or semi-distributed basis whilst physically-based models are little used in real-time applications. However, grid-based physical-conceptual models are increasingly used for real-time forecasting for ungauged catchments
- Flow routing techniques include hydrological approaches, such as the Muskingum-Cunge and kinematic wave methods, and hydrodynamic models. Run-times are sometimes an issue for hydrodynamic models but can usually be resolved by improving the stability and convergence of the model and removing unnecessary detail. Hydrodynamic models are often used where complicating factors such as structure operations and tidal influences affect water levels and hence the flood risk

- Subject to data quality, data assimilation is widely recommended for use in real-time flood forecasting applications and the main approaches are input, state, parameter and output updating. State and output updating techniques are the most widely used approaches although parameter and input updating techniques are used in some situations, such as with data-driven and hydrodynamic models. The development of techniques for distributed rainfall-runoff and hydrodynamic inundation models is an active area for research, although some operational techniques have been developed
- Ensemble and probabilistic techniques are increasingly used in flood forecasting applications and provide the potential for better decision-making when issuing warnings, using more of a risk-based approach. There are an increasing number of operational systems worldwide with much ongoing research to develop and improve the techniques for generating and interpreting outputs
- Flood forecasters typically use information from a range of sources when interpreting the outputs from flood forecasting models, including observations, discussions with colleagues, and local knowledge. Other operational tasks typically include checking and improving model outputs, performing scenario (or 'what-if') model runs, and providing advice to end users. However forecasts are normally only one component in the decision-making process when deciding whether to issue flood warnings
- Forecast verification techniques are widely used as a way of monitoring the performance of flood forecasting models and identifying areas for improvement. Both hydrograph-characteristic and threshold crossing measures are used. Additional measures are required for evaluating the performance of probabilistic or ensemble forecasts.
- Flood forecasting models are normally operated on a flood forecasting system. This typically gathers data, schedules model runs, and presents model outputs in graphical, tabulated and map-based formats. Systems need to be resilient to data losses and model failures and to other problems such as power cuts and communications failures

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Chapter 6
Flood Warning

Abstract For a flood warning service to be effective, warning messages need to be issued to the right people in time to take actions to reduce or avoid the risk from flooding. The information provided also needs to be easy to understand and meet the needs of many different groups, including the public, emergency responders and civil protection authorities. Well-defined procedures also need to be in place to decide when to issue warnings, and decision support systems are increasingly used as part of this process. This chapter provides an introduction to these topics and includes a discussion of recent developments in warning communication technologies and a brief review of some key findings on the social response to flood warnings.

Keywords Flood warning procedures • Warning dissemination • Warning Messages • Social response • Decision Support System

6.1 Introduction

Previous chapters have discussed the main techniques for monitoring and forecasting rainfall and catchment conditions. For flash floods, a key objective is then to use this information to decide which groups to warn to reduce the risk to people or property. If sufficient lead time is provided, it is sometimes also possible to reduce the extent of flooding through operating flood control structures and flood fighting activities.

As discussed in Chap. 1, there is no standard pattern for the organization of a flood warning service and the approach used differs widely between countries.

K. Sene, *Flash Floods: Forecasting and Warning*, DOI 10.1007/978-94-007-5164-4_6,

Table 6.1 Illustration of some typical initial responses to a flood event for a flood warning service

Step	Description
Mobilisation	Initiate round-the-clock staffing of an operations center, alert staff on duty roster, check that key equipment and software is available and working etc.
Monitoring and forecasting	Initiate more frequent monitoring of river, rainfall and other conditions and start more frequent forecasting model runs, using 'what-if' scenarios if appropriate
Operational response	In some organisations, start deployment of staff for levee patrols and on-site monitoring at key locations, and make preparations to operate flood control structures and assist in flood fighting work if necessary
General alert	When appropriate, issue an initial flood watch, flood alert, or similar message, using warning dissemination routes such as the internet, cell phones, radio bulletins and a range of other approaches (see later)
Interagency coordination	Hold discussions with meteorological forecasters, civil protection authorities, emergency responders, the media and others regarding the likely scale and impacts of the event. Issue situation reports and warning updates as needed

For example, warnings can be issued by national hydrological services, civil protection authorities, community leaders, the emergency services and other groups. However, generally there is a core set of activities to perform as a flood starts to develop and Table 6.1 illustrates some typical examples.

Typically following an initial alert for heavy rainfall, additional updates are then issued which in some cases lead to a flood warning when critical thresholds or triggers are exceeded. Figure 6.1 illustrates this process for a flood risk area on a river; in this case the terminology used is to escalate the initial alert to a warning and then to a severe warning, before finally issuing a warning downgrade once river levels start to decrease. However, as discussed later, many other types of flood warning codes are used internationally.

These various procedural, warning dissemination and warning message design issues are discussed in more detail in this chapter, together with some potential advantages from using decision support systems as part of this process. Further background can be found in the references cited which include several guidelines and manuals on these topics; for example describing the approaches used in the USA (USACE 1996; FEMA 2006), Australia (Australian Government 2009) and internationally (NOAA 2010; World Meteorological Organisation 2005, 2010, 2011). Box 6.1 also describes a long-established local flood warning system in the USA which has a strong focus on community engagement. As discussed later this is usually a key contributing factor to the success of any flood warning service, particularly for flash floods.

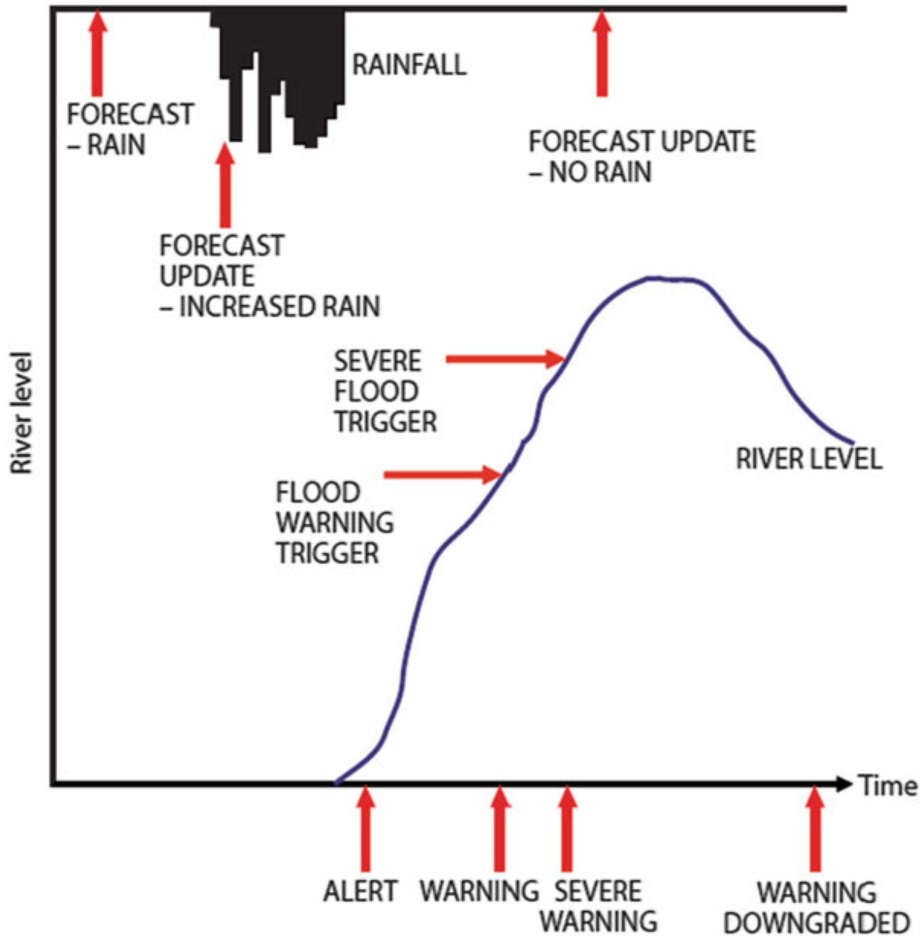


Fig. 6.1 Flood forecasting and warning schematic (World Meteorological Organisation 2011, courtesy of WMO)

Box 6.1 Flood Detection and Warning, Chemung River Basin

Since 1981, Chemung and Steuben counties in New York State have operated a community-based flood warning service (http://www.highwater.org/). This was expanded in 2007 to include neighbouring Schuyler County. The current service covers approximately 250,000 people in the Chemung river basin within a total catchment area of approximately 6,600 km^2, and includes the cities of Elmira, Corning and Hornell. Funding for the scheme is provided by the three counties and from local communities and industries.

The main flood risk arises from the Cohocton, Canisteo, Cowanesque, Tioga and Chemung rivers, which are all tributaries of the Susquehanna River. For example, during Tropical Storm Agnes in June 1972, approximately 250–450 mm of rainfall fell in western New York State and the cities of Corning and Elmira were particularly affected by flooding. Due to the fast response of many catchments, flash flooding is a particular risk and ice jams can also lead to flooding in the winter and spring months.

(continued)

Box 6.1 (continued)

Table 6.2 Key partners in the Chemung Flood Detection and Warning Service

Organisation	Key contributions
Emergency Management Offices (Chemung, Schuyler and Steuben counties)	Provision of emergency weather notifications, coordination of dissemination of warnings and the emergency response; monitoring of river gauges during an event
Environmental Emergency Services Inc. (EES)	Not-for-profit corporation which operates the flood warning service, including the network of river, weather station and precipitation telemetry gauges and simplified computer-based flood forecasting models
New York State Department of Environmental Conservation	Provision of emergency weather notifications; monitoring of river gauges during a flood event; issue of authorisations for emergency actions such as clearing debris from watercourses and channel modifications
NOAA/National Weather Service	Rainfall and severe weather forecasts, flood forecasts for major rivers, weather radar observations, Flash Flood Guidance information, NOAA Weather Radio alerts
U.S. Army Corps of Engineers (USACE)	Real-time data for the Hammond, Tioga, Cowanesque, Almond, and Arkport dams and from USACE precipitation and river gauges; reservoir operations to reduce flooding further downstream
U.S. Geological Survey (USGS)	Real-time river level and discharge data from USGS stations in the basin
Flood Operations Volunteers	Volunteers trained in local flood operations to staff the EES emergency operations centre to collect data and provide consolidated reporting to the three county emergency operations centres. This would also include local flood modelling to supplement the NWS forecasting.

The Emergency Operations Centre is located at Corning Fire Station in the city of Corning and the system is operated by trained volunteers in collaboration with a number of professional partners, as shown in Table 6.2. Activation criteria can include National Weather Service statements on meteorological conditions, automatic rain gauge alarms (1 in./h or more), river gauge thresholds, or observer reports. The following four levels of response are defined:

- Level 1 Inactive – Automated data collection
- Level 2 Standby – Keep in touch
- Level 3 Activated – Skeleton staff at the Emergency Operations Centre until released
- Level 4 Activated – Full staff at the Emergency Operations Centre with 24-h coverage until released

The system is designed to complement that operated by the National Weather Service (e.g. Fig. 6.2), but covering more communities and providing earlier and more targeted warnings to locations at risk plus additional resilience

(continued)

Box 6.1 (continued)

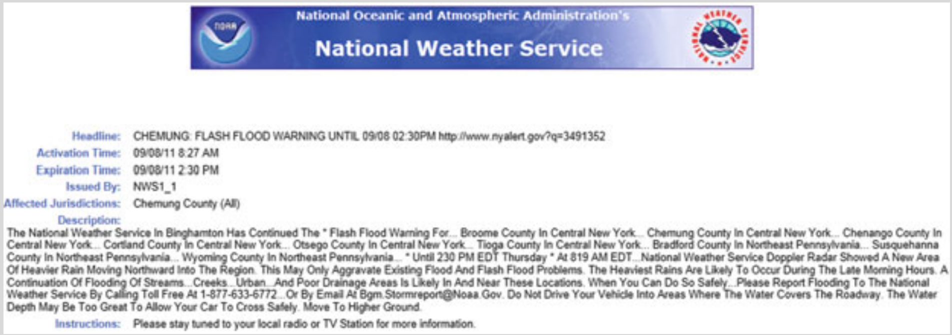


Fig. 6.2 Example of a flash flood warning issued for Chemung County by the NOAA/ National Weather Service in September 2011 during Tropical Storm Lee. This copy of the message was displayed on the New York State All-Hazards Alert and Notification web-based portal, which can also provide alerts by cell phone, email, Twitter ® and other technologies http://www.nyalert.gov/home.aspx

and backup. The community-based self-help approach also encourages local support and interest, both raising public awareness of the steps which can be taken to reduce flood risk and of the actions to take during a flood event. For example, historic flood level signs have been installed in some locations to raise awareness of flooding risk, and 'Turn Around: Don't Drown' signs at some flood-prone highway locations. The successful operation of the system also permits communities to apply for reduced household insurance premiums under the Community Rating System (CRS) within the National Flood Insurance Program.

The telemetry network includes 30 precipitation gauges, 9 climate stations, 11 river gauges, and 1 lake level gauge (e.g. Fig. 6.3). Radio-based telemetry is used. Observations can be viewed at the Emergency Operations Center and are also distributed using the Integrated Flood Observing and Warning System (IFLOWS) system, which provides a wide area communications network for more than 1,000 local flood warning gauges, primarily in the northeast of the United States (http://afws.erh.noaa.gov/afws/).

For additional resilience the telemetry and communications networks include several layers of redundancy in case of failure; for example four of the locally operated river gauges are co-located at the sites of U.S. Geological Survey (USGS) gauges, which also allow observations for those locations to be received more quickly at the operations centre. Due to the fast response of many catchments, information is distributed as soon as it is available, with more detailed or precise estimates provided once they become available, such as flood forecasts from the National Weather Service.

(continued)

Box 6.1 (continued)

Fig. 6.3 Examples of telemetry gauges used for flood warning showing a lake level gauge (*left*) and downward-looking ultrasonic river level gauge (*right*) (Sprague 2010)

The information on river conditions and flood forecasts is made available to the county Emergency Management Offices, state flood control staff, city managers, mayors, and local radio and television stations. Flood Protection and Emergency Plans are also initiated when required and document the procedures for providing warnings to residents and businesses and for flood fighting activities such as closing flood control gates and installing temporary flood walls or berms.

Some key ingredients in the success of the service have included active communication between agencies and with the public, public awareness campaigns and emergency response exercises, and encouraging a two-way collaboration between organisations. For example, the Emergency Operations Centre acts as a clearing-house for basin-wide information and also provides data from telemetry gauges to the National Weather Service for use in flood monitoring and forecasting more widely in the Susquehanna River basin.

6.2 Flood Warning Procedures

The decision to establish a flood warning service for a region or country is often a significant undertaking, so that usually a step-by-step approach is used, expanding and improving the system over time. For example, World Meteorological Organisation (2011) notes that the duties of staff working in flood forecasting services typically include operational activities (e.g. making forecasts), modelling (e.g. model calibration), hydrometry (e.g. data collection, transmission, management and quality control), and informatics (e.g. equipment and system operation, providing appropriate output formats). In some organisations, responsibilities extend to issuing warnings directly to the public and to operational responses such as levee patrols and flood fighting. This may also include providing warnings for other types of water-related hazard, such as pollution incidents and droughts.

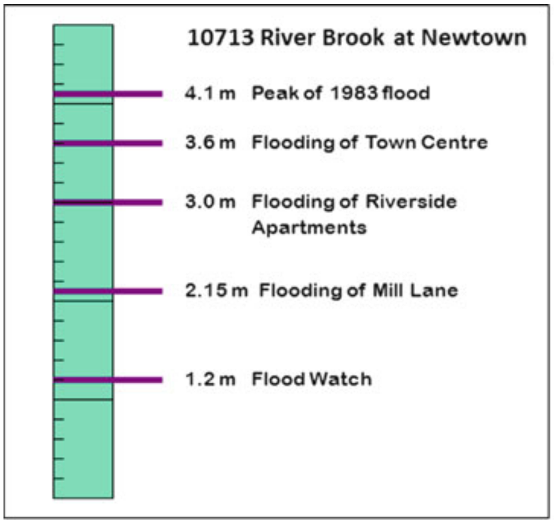
Flood warnings are usually issued from a central location such as an operations centre, forecasting centre or control room (e.g. Australian Government 2009; NOAA 2010; Holland 2012; World Meteorological Organisation 2008). In a national or regional centre, this is typically equipped with computer displays, telemetry and communications equipment, operating manuals, a meeting area, and a range of visual aids such as display screens, maps and whiteboards. In many cases separate computers are dedicated to each key task – such as for flood forecasting or telemetry systems – with backups available in case of failure. Alternatively a networked server-based solution is used. Backup power supplies and communications equipment are normally provided with air temperature and humidity control. In some organisations a separate backup centre is maintained some distance away to provide additional resilience (see Chap. 5). A separate media briefing room may also be available.

For a national or regional warning service, and larger community based systems, there are typically several people on duty at any one time during a widespread flood event. Additional staff may also need to be brought in from other parts of the organization, including specialists to provide computer, software and hardware support. In some countries, specialist technical teams are also on call for advice; for example, in Japan a national Technical Emergency Control Force is maintained specifically to "assist municipalities with collecting information, reducing further damages and starting recovery efforts from typhoons and earthquakes". For trans-boundary rivers there may also be a need to liaise with counterparts in neighbouring countries.

During other periods, staff normally contribute to the many 'preparedness' activities discussed in Chap. 7, and this can often be a full-time activity. Typically the tasks required include improving systems, increasing the extent of the warning service, raising awareness of its benefits, supporting research and development initiatives, and community engagement activities. Many national services also provide technical support and training to community-based flood warning systems. Another key requirement is usually to maintain and update the operational procedures which are used during flood events. These are often called flood warning procedures, operating manuals or standard operating procedures and Table 6.3

Table 6.3 Some examples of the topics which are often included in operational flood warning procedures (usually contained in several documents)

Item	Description
Action tables	Action or Flood Intelligence Tables for deciding when to issue warnings together with instructions for disseminating warnings (format, content, recipients etc.), including the criteria for escalating the state of alert, and possibly for operational actions such as levee patrols and flood gate operations (see below)
Asset condition reports	Findings from recent asset inspections and post event reports regarding any factors to be aware of, such as flood control structures which are temporarily out of operation, debris accumulations in watercourses, and works in progress at levees
Contingency arrangements	Arrangements in case of loss of access to key locations due to flood water, and for telemetry, forecasting or communication equipment failures, in some cases including instructions for relocating to a backup control centre
Debriefing	Arrangements for structured debriefings of flood warning, forecasting and operational staff after – and possibly during – events to provide a record of actions taken, problems encountered and issues to resolve immediately or for the future
Flood data collection	Procedures for high flow gauging and other monitoring and recording activities which should be performed if time permits (see Box 6.2)
Flood warning areas	For each location in receipt of a warning service, additional background information such as descriptions of the neighbourhoods at risk, the areas affected in previous flooding incidents, critical infrastructure in the area, maps showing the estimated flood extent at different gauge levels, and photographs of key locations
Health and safety	Procedures and safety advice for working in or near water (including contaminated water) with maps of safe access and escape routes at key telemetry sites, flood control structures and other locations, and procedures for the use of protective and safety equipment
Multi-agency coordination	Key contact details and protocols for liaising with the media and other organisations. In some countries this includes contacts with operational staff, community representatives and 'spotters' for on-the-ground information; see Chap. 7
Operational instructions	Operating instructions for key monitoring, forecasting, communications and warning dissemination equipment. Also, where this is part of an organisation's responsibilities, operating instructions for flood control gates, temporary or demountable barriers and other flood defence assets, and arrangements for on-site inspections and patrols
Roles and responsibilities	Descriptions of the roles and responsibilities for key staff, call-down arrangements, and handover arrangements between shifts, including updating situation reports, providing briefings, and transferring any shared communications or other equipment
Situation reports and logs	Procedures for record-keeping, issuing situation reports and maintaining communication, flood warning and other incident management logs, typically using handwritten forms and/or electronic data-entry procedures



Level (m)	Description
1.2	FWAT02 Flood Watch
1.8	FW021 Mill Lane
2.7	FW022 Riverside Apartments
2.9	OPS022 Close Flood Gates 1 to 4
3.2	OPS023 Loud Hailer Patrol
3.3	FW023 Town Centre
4.1	INFO23 Peak of 1983 flood
1.8 and falling	AC021 All Clear
	FWAT = Flood Watch FW = Flood Warning OPS = Operational Instruction

Fig. 6.4 Hypothetical action table showing how levels at a river level gauge correspond to flooding impacts, and an associated system of flood watch, flood warning, operational and information thresholds (Adapted from Sene 2010)

shows some examples of the types of entries which are included. As discussed in Chap. 7, the availability of well-defined and rehearsed procedures is particularly important for flash floods due to the speed at which events develop, leaving little time for finding information or deciding on the steps to take.

The amount of information provided varies widely between organisations and – in some cases – just a simple checklist may be sufficient. However, for a regional centre providing a flood warning service for many towns and cities, the associated documentation sometimes extends to hundreds or thousands of pages. Typically this is made available via computer files or a web-based document management system with paper-based copies as a backup in case of power failures or other problems. To help to ensure consistency, tasks are increasingly performed within the framework of a quality management system, with work instructions, directives, checklists and other management tools for each of the main procedures to be followed.

In most flood warning procedures, action tables are a key component and provide lists of pre-defined critical thresholds at telemetry sites, together with the actions to take when values are exceeded. Typically a range of values is provided which correspond to the different stages or phases of a flood alert, as illustrated in Fig. 6.4 for a river monitoring location. However, the types of gauges used and threshold criteria and warning codes used depend on the application and Chaps. 8 to 11 provide examples for several types of flash floods. Also, the amount of discretion which staff can use as thresholds are exceeded depends on the legislative environment within which a flood warning service operates, and ranges from the option to use expert judgement through to a more procedural approach.

As discussed in Sect. 6.5, more complex rules are sometimes programmed into a decision support system, and probabilistic approaches are increasingly being used or evaluated (see Chap. 12). Computer- and paper-based charts and look-up tables are also often used for situations where a single threshold value cannot be defined; for example, when the extent of flooding depends on two or more factors, such as river and tidal levels, the flows in two or more tributaries, or levels upstream and downstream of a flow control structure. Flood forecasting models are also widely used, including simpler rate-of-rise, correlation and other empirical approaches (see Chapters 5 and 8–12), requiring additional threshold values to be defined for these outputs.

Despite the increasing use of computerized systems, in most organisations the decision to issue a warning is still usually taken by a duty officer, rather than automatically. However, automated alerts are sometimes used in applications where there is little or no time available for manual intervention, or where the risks from an incorrect warning are low (see Chapters 1 and 8–12). Another possibility is to allow authorized staff to record or send information messages directly from site via cell phone or tablet or laptop computer for automatic inclusion in helpline messages and web-based warnings. Also, as discussed in Chap. 7, observations and feedback from trained observers, local authorities, emergency agencies and the public are increasingly used to help to monitor a flood as it develops, and are particularly useful for flash floods. Flood warning procedures therefore often include a discussion of how to use and interpret this information, in some cases making use of internet-based decision support systems (see Sect. 6.5).

Box 6.2 Flood Data Collection

As indicated in Table 6.3, flood warning procedures often include actions to take to assess the severity and impacts of a flood. Normally the caveat is included that any such activities should only be considered when time permits and where this will not hinder the emergency response. The resulting information is typically used for post event reviews (see Sect. 7.4) and to help with developing improvement plans (see Sect. 7.7). Some examples of the types of activities which could be performed include:

- Aerial survey – commissioning helicopter- or aircraft-based camera or video surveys of flooded areas, or requesting assistance from the media, police, search and rescue and other organisations operating in the area
- Asset survey – recording and taking photographs of seepage, overtopping and other issues at flood defences, flood control structures and other assets, and with flood fighting equipment such as pumps and sandbags
- Flood damages – collating descriptions and photographic records of the levels reached at properties and critical infrastructure and of the flooding impacts on people and property (to be supplemented after the event by more formal surveys)
- Flood markers – placing metal posts or other markers and/or painting marks on roads and buildings to note the extent of flooding for survey after the event
- Key Records – saving copies or taking digital photographs of paper-based, whiteboard and other notes and records made during the event, including key computer displays and incident, flood warning and communications logs
- Spot flow gaugings – taking measurements using current meter, ADCP or other equipment to help with assessing peak flows and assist with future

(continued)

Box 6.2 (continued)

rating curve development, in some cases allowing for night-time operations by providing appropriate lighting equipment

- Voluntary observations – requesting trained observers such as 'spotters' to send information on rainfall and river conditions and flooding impacts by phone or radio or via data entry into a website

Although during a flash flood there can be limited time for some of these activities, with suitable planning many are feasible. Another possibility is to establish call-down and other arrangements with organisations close to areas where flash flooding is likely to occur, such as for aerial- and ground-based surveys. With suitable training and safety equipment, community, civil protection and other local staff are often able to help with some tasks.

As discussed in Chaps. 8 to 12, in some flood warning and meteorological services, a pool of mobile equipment is maintained to be deployed as events start to develop if time permits (e.g. on receipt of a typhoon warning). Examples include temporary river gauges and debris flow detectors (e.g. geophones). Also, immediately following an event, additional survey and data capture activities are normally performed to assist with post event reporting, as discussed in Sect. 7.4, and are usually coordinated with wider efforts to assess requirements for the recovery and disaster relief effort.

Regarding volunteer inputs, a well-structured programme can potentially provide much useful information to assist both with the warning process and for post event analyses. One example is the extensive SKYWARN program in the USA http://www.skywarn.org/ which has approximately 300,000 locally-administered volunteers who provide observations of severe weather, including flash floods, hail, hurricanes, lightning, thunderstorms and tornadoes. For example, in the related area of tornado warnings, in a survey of emergency managers in Oklahoma, about half reported that tornado spotters in that state are able to operate independently (i.e. to 'self-deploy'). The volunteers included public officials (police, fire), SKYWARN trained spotters and amateur radio operators, and communications were primarily by cell phone, radio and/or amateur radio (League et al. 2010).

In another approach, since 2006 the National Severe Storms Laboratory in the USA has operated a programme to call residents and businesses during or soon after events regarding the occurrence and severity of hail, wind, tornado, and flash flood events. Phone calls are targeted on the basis of thresholds being exceeded, reports of other types of hazards occurring, and any flash flood warnings or urban/small stream advisories which are issued (Ortega et al. 2009; Gourley et al. 2010). Calls are made from an operations centre equipped with several workstations, plasma screens and call stations and recipients are selected from maps which summarise the current situation combined with a database of georeferenced contact details. The types of information collected include the depth and extent of flooding, the number of evacuations, and the time of onset and duration of flooding.

6.3 Warning Dissemination

6.3.1 Techniques

For issuing flood warnings, many different approaches are used ranging from the latest technologies to traditional methods such as door-knocking and phone calls. These are usually categorized according to whether warnings are issued directly to the people and groups likely to be affected, or more indirectly using the media and other routes; for example, based on the following approaches:

- Indirect – warnings issued using general approaches such as radio (including tone-alert systems), television, the internet, and toll-free telephone help lines
- Community – warnings issued to part or all of a community using methods such as alarm bells, message boards, megaphones, electronic signs, sirens (e.g. Fig. 6.5), and public address systems (fixed, vehicle, helicopter)
- Direct – warnings issued directly to individuals by methods such as phone (cell, landline, satellite), text message, hand-held radio, door-knocking, and email

Some alternative terms which are used include specific/general (Australian Government 2009), broadcast, community and individual (Andryszewski et al. 2005), and push/pull or proactive/reactive (Martini and de Roo 2007).

For direct warnings, lists, spreadsheets or databases of contact details are normally generated based on flood risk maps and consultations with civil protection authorities and other groups. For residents in flood prone areas, the option is sometimes provided

Fig. 6.5 Example of a flood warning siren in the Upper Calder valley in Northeast England: the river lies between the two flood walls in the background

Table 6.4 Some examples of websites for disseminating flood warnings

Country	Organisation	Website
Australia	Bureau of Meteorology	http://www.bom.gov.au/australia/flood/
Bangladesh	Flood Forecasting and Warning Centre	http://www.ffwc.gov.bd
England and Wales	Environment Agency	http://www.environment-agency.gov.uk
France	SCHAPI	http://www.vigicrues.gouv.fr/
Scotland	SEPA	http://www.sepa.org.uk/
USA	NOAA/National Weather Service	http://weather.gov/

to subscribe (or 'opt-in') to the warning service or – in order to increase the uptake of the service – to 'opt-out' only if warnings are specifically not required.

In recent years, developments in cell phone and broadcasting technologies, the internet and social networking have greatly increased the choice of methods available. Some of these techniques are of particular interest for flash floods due both to the potential time savings in issuing warnings and the ability to target warnings to large numbers of people, including when they are away from home or work. For example, in some warning dissemination systems, text or recorded messages can be sent automatically to all cell phone numbers in a database, including alternate contacts if no confirmation is received. Some cell providers are also able to issue text messages to all subscribers within specific geographic areas using cell broadcasting techniques. Some internet-enabled (smartphone) applications also allow users to view location-dependent weather and flood warning information based on GPS or cell-tower triangulation.

Many organisations now also maintain a website to display flood warnings and Table 6.4 shows some examples. Typically web addresses are publicized in television and radio bulletins and as part of wider public awareness campaigns. In some cases this includes the option to subscribe to RSS (Really Simple Syndication) feeds. For authorized users, in countries such as the USA web-based chat rooms are increasingly used by forecasters, emergency managers, the media and other parties.

Flood warning messages are now also more easily included in television and radio broadcasts. For example, in the first nationwide test of the Emergency Alert System in the USA during 2011, a test message was sent to "……broadcast radio and television stations, cable television, satellite radio and television services and wireline video service providers across all states and the territories of Puerto Rico, the U.S. Virgin Islands and American Samoa" (http://www.fema.gov).

Although not universal, some of these approaches can be used even in the poorest communities due to the huge increases in cellphone coverage and usage in recent years. Satellite-based and high frequency radio systems are also potentially useful for disseminating warnings to remote, rural communities, although satellite phones still remain an expensive option. For example, for many years the international RANET project (Sponberg 2006) provided climate and weather related information via satellite transmissions to large parts of Africa, Asia and the Caribbean, with information disseminated onwards via computers, digital radio, wind-up radios, cell phones and other devices.

However, traditional approaches such as drums, flags, whistles, gongs, horns and bells still remain widely used in rural areas. Hand-operated sirens and megaphones, community radio stations and motorcycle or bicycle messengers provide other options. For example, in Bangladesh, more than 40,000 village volunteers work for the Cyclone Preparedness Programme and are equipped with hand-operated sirens, megaphones, transistor radios, signal lights, flags, and first-aid and rescue kits (e.g. World Bank 2011). Indigenous approaches are also often important; for example, some communities may have long experience of flooding and be knowledgeable about early warning signs such as the changes in water colour and drops in river level which sometimes precede debris flows (see Chap. 9). Similarly, for river flooding, some other indicators which are used (in addition to heavy rainfall) include waterlogged soils and unusual patterns of animal movements.

More generally, social networks provide another opportunity to issue warnings to large numbers of people, and allow two-way communications between organisations and the public. For example, in the USA, hurricane and flood warnings are routinely disseminated using Twitter, Facebook and other media, and blogs and crowdsourcing are other options. In South Africa, for example, amateur radio operators maintain a blog providing weather warnings, news and reports of floods and other natural disasters (http://saweatherobserver.blogspot.com/). Also, during the Haiti earthquake in 2010, a crowdsourcing approach was used whereby incidents reported by text message to an emergency number in the local language (Kreyol) were translated by volunteers. These were then georeferenced for display on a website with the result that 'the average turn-around from a message arriving in Kreyol to it being translated, categorized, geo-located and streamed back to the responders was 10 min' (Munro 2010).

Multimedia systems provide another option to rapidly disseminate information by a wide range of methods, including email, phone, and text messages. Typically these consist of off-the-shelf systems for multi-hazard applications, or custom-made applications specifically for flood warning. Some examples of the types of options which are potentially available include the facility for text-to-voice conversion to generate synthetic voice-based warning messages, and the option to issue the same warning message in multiple languages by text or voice. Performance monitoring tools are usually also included for use in post event analyses; for example providing summaries of the numbers of people reached, the number of repeat attempts to make contact, and the times taken for each successful contact.

6.3.2 Choice of Approach

The approaches which are used depend on organizational policy, the budgets available, cultural factors, reliability and a range of other issues. In any society another consideration is that there are usually some groups without access to computers, cell phones and similar technologies: the so-called digital divide (e.g. Parker 2003). However, flood warning agencies are increasingly able to offer warnings via a number of dissemination routes, allowing users to select the methods which best suit them and providing backup routes in case the preferred methods fail during a flood event.

In particular, for civil protection authorities and emergency responders, it is often essential to know that a warning has been received, which typically limits the options available. For example, in addition to direct phone calls and visits, other possibilities include emails and text or voice messages requiring a response; however, for the more automated approaches, maximum time limits need to be set for receipt of a reply, following which a direct call is made or an alternate contact selected.

These various approaches are of course also used to provide warnings for other types of natural and technological hazards – such as tornadoes, earthquakes and wildfires – and their strengths and limitations are generally well understood (e.g. Sorenson 2000; Coleman et al. 2011). However, for flash flood warning applications, Table 6.5 summarises some particular factors to consider based on these and other citations in this chapter.

The question of resilience is particularly important and – as discussed in Chap. 7 – there have been many examples of flood events in which communication routes have failed. For example, during flood emergencies, networks are sometimes overloaded, key telecommunications hubs flooded, and power supplies interrupted. Also, many publicly available services such as cell-phone networks and broadband links are only offered on a best endeavours basis, and may fail when they are most needed. For safety-critical communications, this could then require installation of a robust primary or backup emergency communications network where one is not already available; for example using leased line, high frequency radio or satellite links. To help to overcome these problems, multiple warning dissemination routes are therefore also widely recommended.

The time taken to issue warnings is another key consideration. As discussed in Chaps. 1 and 7 – this needs to be factored into the overall design of the system since it directly affects the time available for an effective emergency response. For example, warning response curves or diffusion relationships are sometimes used to assess the proportion of people notified as a function of time for each option considered (Rogers and Sorenson 1991), particularly for dam break emergencies. Some key factors to consider include the number and locations of people requiring warnings and the staff time required for each contact.

The overall time required can then be estimated by past experience, trial runs, or observed during emergency response exercises or actual flood events. For example, a door-to-door approach, although effective, is often time consuming, as is manually calling large numbers of people by phone. Indeed, even automated phone dialing systems sometimes take several minutes or more to reach a large number of recipients, particularly if many repeat or alternate calls are required if there is initially no response. For telephone-tree or cascade systems – in which the first people warned inform others – there is also a risk that key people will be unavailable or phones not working or switched off, introducing further time delays into the process. The time of day is another factor to consider and the early issue of initial alerts and watches can increase the likelihood that people will continue to monitor the situation at times when they are away from home, or late at night when televisions, cell phones, computers and other devices are normally switched off. Also, if time

Table 6.5 Some examples of factors to consider when selecting warning dissemination approaches for flash flood applications

Topic	Description
Audibility	When sirens, bells and other audible techniques are used, are they likely to be heard against a backdrop of high winds and/or heavy rainfall and/or by the hard of hearing and/or through double glazing and other insulation? Also, as discussed in Sect. 6.4, will recipients understand the meaning of the alert?
Availability	Will the warning reach those with the authority to take decisions on protecting people or property; for example when they are at work or travelling, when people are asleep, or when electronic devices are switched off or out of range?
Dissemination time	How long is it likely to take for all recipients to receive a warnings after the decision has been taken to issue it and how many – if any – requests for authorization are required as part of that process, potentially introducing additional time delays?
False alarms	If the alerting method is triggered automatically – for example by activating a siren when a river level threshold is exceeded – what is the risk of false alarms and what are the possible consequences in terms of public confidence and the risks from unnecessary evacuations of vulnerable groups in hospitals, nursing homes etc.?
Flood risk	For methods which rely on access to properties or equipment, is there a risk of roads and paths being impeded by flood waters and hence to the safety of staff or volunteers?
Media broadcasts	For radio and television networks, can messages only be issued at set times (e.g. during news bulletins) or are interrupt, overlay or cut-in facilities available for urgent messages, with the facility to display streaming or crawler messages as well?
Resilience	How reliable is the method likely to be under conditions of heavy rainfall and/or flooding, considering the transmission method itself, possible power failures, flooding of relay stations and other factors? Are back-up power or battery facilities available? Are users still able to request/receive test messages during the possibly lengthy periods between flood events to check that systems are still working?
Signal reception	Can cell phone, radio or other signals be received in all locations where a warning service is offered, such as in steep mountain valleys prone to flash floods?
Time of day and season	Has the effectiveness of warning dissemination procedures been considered from the point of view of the time of day or night, during working and non-working hours, and in summer and winter?
Transient populations	How will people be notified when they are away from their usual place of work or residence, or are 'on-the-move' such as tourists, business travellers, seasonal workers, vehicle drivers and hikers? (see Chapter 12 for a further discussion of this topic for the case of road users)
Vulnerable groups	Does the proposed approach cater for those with special requirements/needs; for example, the visually impaired, disabled, hard of hearing, children, foreign language speakers, and others?

permits, visits in-person or personal phone calls are often required (and appreciated) for more vulnerable members of the community to explain the situation and provide assistance if required.

More generally, as in other areas of flood risk management, a risk-based approach can be useful when choosing the methods to use, with more resource intensive (staff time, cost etc.) techniques selected where the risk is highest. For example Andryszewski et al. (2005) note that, in addition to a website and helpline, methods for high, intermediate and low risk situations could include the following approaches, expressed in terms of a level of service:

- Maximum – direct warnings to each property by telephone, fax, e-mail etc. using a computer-based warning system
- Intermediate – use of loudhailers or sirens in each community
- Minimum – use of the media to broadcast warnings

In some cases, subcategories may also be introduced; for example, for high risk situations, using a different approach where the probability of flooding is low but the potential consequences are high, such as overtopping of flood defences in a city, compared to high probability low consequence situations, such as frequent flooding of isolated properties (although with risk to life overriding these factors).

Of course, cost is another factor to consider and – depending on the approaches used – this typically includes not just the initial installation or purchase costs but ongoing expenses such as call charges, connection charges, licence fees (e.g. for radio-based methods) and support, maintenance and repair costs. However, in some cases there may be opportunities to offset some items; for example if service providers are able to offer support as part of Corporate Social Responsibility programmes.

Further background on the methods used and typical costs is provided in several of the guidelines and reviews referred to in this chapter. Also, some examples of the techniques used are presented in Box 6.1 and in several of the case studies in other chapters, including examples from France, Japan, Nepal, the Philippines, and the USA.

6.4 Warning Messages

6.4.1 Interpretation of Warnings

When issuing flood warnings, another key consideration is the information to convey and how that is interpreted by the public, emergency responders and others. Much social research has been performed on this topic for flash floods and other types of fast-developing ('short-fuse') hazards, such as tornadoes. However, in some cases, post-event surveys have suggested that a surprisingly small proportion of those receiving warnings subsequently took appropriate actions to protect themselves or others (e.g. Drabek 2000; Handmer 2002; Betts 2003; Parker 2003; Parker et al. 2009). By contrast, self-help, unofficial or informal approaches are often shown to play a valuable role; for example, with residents watching river levels and contacting others who are potentially at risk.

The reasons for not responding to warnings are varied but typically include an inability to respond (e.g. through disability), a lack of confidence in the authority providing the warnings, misunderstanding the message, and cultural issues. For example, as noted by Mileti (1995), 'people who receive warnings first typically go through a social psychological process to form personal definitions about the risk they face and ideas about what to do before they take a protective action. The process is readily divided into several phases:

- hearing a warning,
- forming a personal understanding of what was meant by the warning
- developing a level of belief in the risk information conveyed in the warning
- personalizing the risk or perceiving *it* to be someone else's problem
- deciding what if anything to do and responding in ways thought to be appropriate for the risk personally faced'

Other factors which are often noted include the fear of looting of property, contradictory information, and irrational or risk-taking behavior. In addition Keys (1997) notes that "The community is not a single mass of people but is stratified in terms of degree and type of risk, past experience, language and other differentiating characteristics". Similarly, NOAA (2010) notes that "the general public" is not a homogeneous group since it involves:

- Decision makers at all levels in the community
- People with many different levels of education
- People with many different levels of financial ability and responsibility
- People of different races and beliefs
- People with many different primary languages
- People with widely varying experience with the hazard
- People with varying levels of physical ability

This therefore requires a range of different approaches both for issuing warnings, and when designing public awareness campaigns.

For these and other reasons, the findings from surveys of people at risk from flooding – or who have recently experienced flooding – sometimes differ between groups and locations even in the same country, as shown by examples from Australia (Pfister 2002, Betts 2003), the USA (Hayden et al. 2007), the UK (Twigger-Ross et al. 2009) and for several European countries (Parker et al. 2009). Despite these difficulties, some general principles emerge and are discussed in the following sections. More generally, in the context of severe weather warnings, Gunasekera et al. (2004) note that some ways to reduce (or mitigate) the impacts of natural hazards include:

- Further increasing the emphasis on extending the lead time of warnings
- Improving the accuracy of warnings at varying lead times
- Satisfying greater demand for probabilistic forecasts

- Better communication and dissemination of warnings
- Using new technologies to alert the public
- Better targeting of the warning services to relevant and specific users (right information to right people at right time at the right place)
- Ensuring the warning messages are understood and the appropriate action taken in response

6.4.2 General Approach

As discussed earlier, flood warnings are usually escalated as an event develops, starting from an initial alert and proceeding to warnings of various severities before issuing an all-clear or downgrade once the risk has passed.

For example, when using rainfall forecasts as part of the warning process, typically a generalized alert is issued as a storm develops using rainfall depth-duration threshold, flash flood guidance or similar approaches (see Chaps. 8 to 11). Although this will not be specific in terms of the timing and location of flooding, it raises awareness amongst the public of the potential dangers, and allows first responders and others to mobilise staff and start with preparations for a possible flood event.

As the event develops, the alert can then be upgraded to a warning and include more specific actions to take. Some recipients may also appreciate warnings at specific times of the day, even in the knowledge that this often leads to more false alarms due to the greater uncertainty at longer lead times. For example, for government organisations, businesses and farmers it is sometimes more convenient to receive warnings during daylight or working hours for logistical or safety reasons, or on weekdays rather than weekends. When using internet, text-based or smartphone based approaches, there is also the opportunity to provide more detail on the status of the warning and the actions to take, and some websites include other useful information such as maps, photographs and live camera feeds.

The flood warning codes and messages which are used are often standardized at a national or organisational level and in some cases are based on extensive social surveys of communities at risk from flooding. For example, in Australia the terms minor, moderate and major flooding are used (see Chap. 8) whilst NOAA in the USA provides the following definitions (see Box 1.1):

- Flash Flood Watch: Conditions are ripe for flash-flooding in the area – not necessarily limited to riverside areas. Watch for heavy rain or rising streams and culverts. Prepare to evacuate immediately.
- Flash Flood Warning: Flash flooding is imminent or occurring. Leave flood-prone areas (which could be as close as a culvert or creek near your house), but DO NOT travel through flood waters.
- Urban and Small Stream Flood Advisory: Minor flooding is expected. Such floods cause significant inconvenience, like blocked underpasses and flooded roads. They can be life-threatening if you don't use basic caution.

- Flood or Flash Flood Statement: The flooding has already occurred, and this information will update you on new dangers, revisions of flooded areas and other information.

The emphasis here on avoiding floodwaters is important since, in some countries, vehicles drivers account for a significant proportion of fatalities in flash floods (e.g. Henson 2001; Jonkman and Kelman 2005; Ashley and Ashley 2008). Depending on the location and context, messages are sometimes tailored to other groups particularly at risk from flash floods, such as hikers, mobile home owners and campsite residents. In some cases, signs are permanently installed within communities to help people relate warning messages to likely flood levels; for example using colour-coded marker boards, road signs showing possible water levels, or plaques on buildings illustrating historical high water marks.

However, even when warning codes are well established, it is still useful to regularly review and assess their effectiveness, particularly as part of post-event reviews of major flood events. For example, in England and Wales, following extensive flooding in 1998, one post event recommendation (Bye and Horner 1998) was that the colour-coded approach in use at that time (yellow, amber, red) was not well understood. A new system was therefore adopted using the terms Flood Watch, Flood Warning, Severe Flood Warning and All Clear, with associated messages and icons (i.e. symbols to appear alongside messages). Following major floods in the summer of 2007, an extensive testing and consultation exercise was then carried out leading to a more intuitively staged flood warning service, commencing with a Flood Alert. The All Clear code was also changed to Warnings No Longer in Force and all messages were updated to convey to the public 'when they need to monitor the situation/be vigilant, when they need to act (and what to do), and also when the incident is over' (Environment Agency 2010).

6.4.3 Message Templates

To reduce the time delays in issuing warnings, and to help to ensure a consistent approach, generally as far as possible the formats, templates and content for warning messages should be pre-defined ('pre-scripted'), and agreed between all key organisations involved in the flood response. This is particularly important for flash floods since the time available for discussion and message preparation is often limited during an event.

This approach also provides the opportunity to consider factors such as style issues, content, tone, terminology and completeness (Australian Government 2009) and to prepare templates in multiple languages, if required. As an event develops, details can then be added on the anticipated location, timing, and severity of flooding, and additional advice provided if unanticipated factors occur. Where event-specific issues do occur, the message to convey should normally be agreed with other key partners if there is time; for example, this is particularly important for high risk situations such as major evacuations, potential dam breaches and the loss of key utilities. Where possible, the general aim is to provide clear, unambiguous messages both to the public and the media. For flash floods, the fast developing nature of the event also often requires close collaboration between meteorologists and flood warning staff in terms of the information which is provided.

Some other considerations in designing warning messages typically include the need to consider the following aspects (e.g. Elliot and Stewart 2000; Martini and de Roo 2007):

- Actions – specific actions which can be taken by members of the public and others and advice on how to obtain further information
- Currency – the date and time of the warning or forecast, its period of validity and the expected time of the next update
- Flood Impacts – the current situation and – if possible – the anticipated location, magnitude and timing of flooding (onset, peak, duration), provided in terms which are meaningful to the recipients, such as the streets and properties which are likely to be flooded, and where possible relating this information to previous flood events
- Source – warnings should originate from a trusted source with contact details for further information (help lines, websites, phone numbers etc.), with several routes of communication to reinforce the message

For example, for early warning systems in general, World Meteorological Organisation (2010) notes that "effective warning messages are short, concise, understandable, and actionable, answering the questions of "what?", "where?", "when?", "why?", and "how to respond?" They should also be consistent over time. Alert messages should be tailored to the specific need of intended users. The use of plain language in simple, short sentences or phrases enhances the user's understanding of the warning. In addition, the most important information in the warning should be presented first, followed by supporting information. They should also include detailed information about the threat with recognizable or localized geographical references".

In some cases, specialized users require additional information, such as on current and recent forecast performance. Some organisations also have pre-defined messages for internal use for operational actions such as closing flood control gates or starting levee patrols. More generally, as discussed in Chap. 7, map-based presentations are a powerful way to convey information; for example showing the likely extent of flooding for different river stages against a backdrop of street maps, and web pages showing the locations of all current flood warnings in a region. In some countries, maps are also provided digitally for downloading in various standard spatial data exchange formats for import to a user's own systems.

Another consideration is how warning messages will be exchanged between organisations. In an effort to provide a more standard approach, the International Telecommunication Union and others have led development of a communications protocol for emergency messages for both natural and technological hazards, called the Common Alerting Protocol (http://www.oasis-open.org/). A standard

XML-based message format is used which includes information on the sender, the period of validity for the message, a description of the hazard, instructions on the actions to take, and the geographic coordinates or polygon boundaries. The specification also allows for digital images and audio messages to be included in messages and information on the following three key items:

- Urgency (time for responsive action immediate, expected, future, past or unknown),
- Severity (threat to life or property extreme, severe, moderate, minor or unknown)
- Certainty (probability of occurrence very likely, likely, possible, unlikely or unknown)

This approach is now widely used in many countries either as the primary warning protocol or alongside existing national and other systems. A register is also maintained of alerting authorities so that information aggregators such as private sector forecasters and web-based map providers have confidence that the messages are from an official source.

For flash flood warnings, one particularly important aspect is the ‘certainty’ entry since – as in other flooding applications – it is generally considered important to convey the uncertainty when issuing warning messages (e.g. World Meteorological Organisation 2009; Australian Government 2009; Martini and De Roo 2007). At the simplest level, descriptive information alone is sometimes provided; for example, the use of words such as ‘may’, ‘probably’ and ‘likely’ is one option, provided that messages include advice on the actions to take (e.g. Australian Government 2009). Also, in the context of all-hazard warning systems, UN/ISDR 2006 suggests using phrases such as “if present conditions continue…” or that “there is an 80 % chance that…”

The next step is to include quantitative information such as “….the probability of flooding exceeds 60%….” or to provide the raw outputs from ensemble flood forecasting models. For example, several national hydrological services already operate ensemble flood forecasting systems (e.g. Cloke and Pappenberger 2009) and the number continues to increase. The aim is normally to improve decision making when issuing warnings and to facilitate a more risk-based approach combining probability and consequences. This approach shows much potential for flash flood applications and some of the message communication and related issues are discussed further in Chap. 12.

6.4.4 Tones, Lights and Barriers

For flash floods, due to the short time available, there is some attraction in using techniques such as sirens, bells and flashing lights which can be activated automatically or via a remote telemetry link. These are typically positioned at access points to areas at risk or, in the case of sirens, distributed in a network within communities. Standard audio or tone alerts indicating the type of emergency are also used in some countries for transmission by radio, television, siren and other means.

However, as noted in Table 6.5, one potential disadvantage with these approaches is that recipients need to understand the meaning of the alert. Typically, this requires both extensive consultations when establishing a warning system and regular public awareness campaigns and training exercises. The effectiveness of these approaches also varies between countries. For example, in the USA there is a long tradition of using sirens for tornado warnings and, to a lesser extent, for flash flood warnings. In Europe, by contrast, the use of sirens varies widely and – in some locations – there has been a gradual phasing out in recent years based on the findings from post-event reviews and social response surveys.

In some cases, though, the meaning is either obvious from the context or additional text- or voice-based information is provided. Examples include remotely activated traffic lights, electronic signs and automatic barriers, and sirens with the facility to broadcast voice messages. Some typical locations where these approaches are used include low water road crossings and at the lowermost end of roads leading into canyons (see Chap. 12), for riverside paths and car parks (see Chap. 10), and in some debris flow and dam break warning systems (see Chaps. 9 and 11). Generally, a key aim is to keep pedestrians and road users from entering areas likely to be flooded, or to warn them to leave those locations as quickly as possible.

In some cases, fully automated approaches based on these techniques are used as a failsafe backup or 'last resort' in case a warning message does not get through. For example, an electrical switch could be used to trigger a siren when a critical level is exceeded. This provides at least some minimal warning lead time, although with a risk of false alarms or missed warnings if the device fails to operate correctly or the threshold values are incorrect. However, as noted earlier, fully automated approaches are sometimes also used where – due to the very short lead times available – there is no other choice, such as in some dam break warning sytems (see Chap. 11). Also, as noted in previous chapters, some meteorological and hydrological services now allow users to register via a website so that alerts are issued automatically by email, text message or synthetic voice message; in some cases with the option to define the river levels thresholds at which messages will be issued. However, when offered, this is normally an information-only service and does not include advice on the actions to take although that is another possibility being trialled (e.g. in the UK) for some fast response catchments.

6.5 Decision Support Systems

6.5.1 General Approach

As a storm develops, or tracks towards a region, this may indicate an increased risk of flash flooding over a wide area.

For a flood warning service, the response then typically includes monitoring and forecasting the conditions at many locations whilst dealing with other activities such as liaison with emergency response organisations and the media, and issuing early warnings. Individual situations may also need particular attention, such as whether residential areas will need to be evacuated and the risks to vulnerable groups in hospitals and nursing homes. More generally, MacFarlane (2005) notes that some particular characteristics of decision making in emergencies include "uncertainty, complexity, time pressure, a dynamic event that is innately unpredictable, information and communication problems (overload, paucity or ambiguity), and the heightened levels of stress for participants, coupled with potential personal danger". Chapter 12 discusses some of these sources of uncertainty in more detail.

To help to deal with this complexity, some flood warning services have developed decision support systems both to ease the load on duty officers, and to contribute to better decision-making during flood events. These typically range from small-scale flood incident management systems operated by a flood warning service alone to larger-scale interagency systems which include flood risk as part of an all-hazards approach. Typically a 2-D or 3-D map-based interface is used to increase spatial awareness of the risks, with multiple ways of accessing the system provided to meet the needs of different users, such as via laptop computers and smartphones. In addition to background maps (streets, rivers, topography etc.), the mapping interface typically includes information on flood warning or evacuation areas, current and forecast conditions, vulnerable groups, emergency response assets, and other key features. There have been several studies into the specific requirements for flood incidents (e.g. Flikweert et al. 2007; Lumbroso et al. 2009) and more generally for all-hazards systems (e.g. MacFarlane 2005; Van Oosterom 2005) and Table 6.6 summarises some typical findings from these types of studies.

As with all safety-critical software, a structured approach to system development is required, with extensive testing at each key stage, and resilience built into the design to cope with power, telemetry and other failures. Systems also need to be integrated into operational procedures with appropriate levels of documentation, staff training and support and maintenance. It is however worth noting that, in most systems, the final decisions are still taken by duty officers based on experience, judgement and confidence in the information provided.

Another key consideration is the extent to which the system acts primarily as a tool for sharing information which has been developed beforehand (e.g. hazard maps), or relies on dynamically generated or modeled information during the event (e.g. maps of the current extent of the hazard). In the first case, there is time to review and audit information beforehand, but event-specific factors sometimes mean that this is not as reliable as that provided by a real-time version. However, in the second case, there is a greater reliance on real-time observations and model outputs with a risk that significant errors will not be noticed in the time available. The time required to operate computer models may also be a constraint.

A related question is the extent to which a system provides advice on the actions to take. To date most operational systems have been developed primarily for viewing information, but optimisation algorithms have been developed in some cases (see below), particularly for evacuation planning. Some examples of the types of the techniques which could be used include artificial intelligence, fuzzy logic and simulation-based approaches.

Table 6.6 Some potential applications for decision support systems in flood warning applications

Item	Description
Critical infrastructure / vulnerable groups	Tools to assist with decisions on warning and protecting critical and vulnerable locations such as water treatment works, power stations, police, fire and ambulance stations, and hospitals, prisons and care homes; in some cases considering the potential consequential risks such as drinking water contamination and the impacts of power cuts on water treatment works and telecommunications
Emergency response assets	Tools to assist with the near real-time tracking and deployment of assets such as pumps, excavators, sandbags, vehicles, boats and helicopters, in some cases using GPS devices.
Evacuation planning	Tools to assist with deciding on the safest and fastest evacuation routes, taking account of current shelter occupancies, flooding and traffic conditions (including real-time traffic flow monitoring), access routes for the emergency services and driver behavior models
Flood asset management	Tools to display the most recently reported condition of flood defence (levee) systems, flood control gates and other assets and to advise on their operation and the requirements for emergency repairs
Flood impacts	Near real-time mapping of flood extent, depths and velocities and likely impacts based on the outputs from flood forecasting models, or alternatively a range of pre-defined maps linked to current or forecast river levels
Search and rescue	Risk-based techniques to assist with identifying and prioritizing the rescue of people, livestock and domestic animals taking account of near real-time information on the emergency response assets which are potentially available
Situation reports	Dynamically updated reports and other documentation, such as flood response plans, incident logs and timelines, accessible to all key responders and available for viewing on mobile devices and websites and by printing hard copies, and including automated recording of actions to maintain an audit trail to assist with the post event analysis

6.5.2 Examples of Applications

Although the use of decision support systems is a developing area, there have been several practical applications for flood incident management, particularly in parts of the Netherlands and Germany (Langkamp et al. 2005; Flikweert et al. 2007), Switzerland and the USA.

For example, the Swiss IFKIS-HYDRO system was developed specifically for flash floods and debris flow incidents and has a focus on small to medium alpine catchments, typically with areas of up to about 1,000 km^2 (Romang et al. 2011). This forms part of a national web-based common information platform for natural hazards available to civil protection authorities and other government organisations (Heil et al. 2010). The flash flood component builds on a long-established approach to managing the hazards from avalanches and displays both quantitative forecasts and observations with more descriptive, unstructured information reported by observers.

Some typical examples of observer feedback might include of flooding of roads, debris collecting at bridges, water levels at specific locations or properties, or sediment barriers forming. Information from past events and recent site inspections is also provided, such as on unstable slopes and accumulations of debris and timber. This approach greatly helps to increase situational awareness during a flash flood event, particularly on smaller catchments with little or no telemetry information available. Intervention plans are also generated showing key infrastructure, transport routes, properties and other locations at risk.

Decision support systems have also been used for many years to help with the response to hurricanes, including any flooding incidents. For example, in the USA, both the Hurrevac system (http://www.hurrevac.com) and Evacuation Traffic Information System have been to assist with emergency planning and response (e.g. Wolshon et al. 2005). Many real-time flood forecasting systems also provide an element of decision support; for example, by allowing 'what-if' scenarios to be performed and flood warning threshold exceedances to be reported (see Chap. 5).

Some further examples are briefly described in Chap. 8 (for reservoir flood control operations), Chap. 10 (for urban drainage control systems), and Chap. 11 (for dam break emergencies). Chapter 12 also discusses some potential applications of ensemble and probabilistic forecasts in decision support systems. More generally, social messaging and crowdsourcing techniques have the potential to provide additional 'on-the-ground' information for input to these types of systems.

Similar systems are increasingly used for meteorological applications and are likely to play an increased role in future to help forecasters to provide warnings for extreme events. For example, Chap. 4 a storm warning decision support system in Finland in which the object-based recognition of storms is assisted by spatial comparisons with emergency incidents recorded on a national near real-time database (Halmevaara et al. 2010).

6.6 Summary

- During the pressure of a flash flood event, there is often little time available for discussions or finding key information. As far as possible, the actions to be taken therefore need to be documented in procedures and discussed and agreed in advance with all groups involved in the warning and response process. In particular, this includes the thresholds and other decision criteria to be used for issuing warnings
- If plans are in place, much useful information can be collected during a flood event on the magnitude, extent and impacts of flooding. This is useful both for post-event reporting and more generally in assessing flood risk and identifying areas for improvements to monitoring, forecasting and warning systems and procedures

- Flood warnings are often classified as direct, community-based and indirect. In recent years the number of options available for issuing warnings has increased dramatically due to improvements in telecommunications, computer systems and other factors. Examples include the use of websites, social media, smartphone applications, and multimedia dissemination systems. Some typical advantages include the ability to send targeted warnings directly and more quickly to larger numbers of people than has been possible in the past
- Normally warnings should be disseminated using a range of approaches. For flash floods, some factors to consider include: audibility, availability, dissemination time, false alarms, flood risk, media broadcasts, resilience, signal reception, time of day and season, transient populations and vulnerable groups. Where possible, any existing informal or indigenous approaches should be integrated into procedures
- Typically a staged or phased approach is taken to issuing flash flood warnings, starting from an initial watch or alert and then proceeding to a warning. The messages, codes and icons used need to be carefully considered following discussions with key organisations and community members, and are often standardised at a national level following international best practice. Increasingly an indication of uncertainty is provided with flood warnings
- There are many reasons why warnings are not always effective and these often relate to the diverse requirements of those receiving warnings, and a range of social and cultural factors. Some steps to help improve success include widespread consultations with community members and other groups, public education campaigns and social research on problems during previous flood events. In particular, the use of pre-defined message templates helps to ensure consistency in the warnings which are issued and to speed up the warning dissemination process
- Map-based decision support systems are increasingly used to provide information to flood warning, civil protection and emergency response staff during flood events. This helps to improve situational awareness and in some cases includes forecast model outputs, incident reports from observers and dynamically updated flood response plans. Systems need to be resilient to communications and other failures and carefully integrated into operational procedures. The provision of operational advice is another option although real-time optimization algorithms of this type have been little used to date

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Chapter 7
Preparedness

Abstract Numerous studies have shown that the effectiveness of a flood warning system can be improved through active community involvement, maintaining up-to-date flood response plans and performing regular reviews and training exercises. These activities fall under the general heading of preparedness. For flash floods, it is particularly important to have plans in place since usually there is little time available for issuing warnings under the pressure of a flood event. This chapter discusses a number of topics in this general area including the techniques used for assessing flood risk, monitoring the performance of a warning system and prioritizing areas for improvement.

Keywords Flood risk assessment • Flood response plans • Post-event reviews • Performance monitoring • Emergency response exercises • Improvement Plans • Flood warning economics

7.1 Introduction

When a flash flood occurs, flood warnings have the potential to reduce the risk to people and property. For example, some actions which can be taken on receipt of a warning include moving property, vehicles and valuables to safer locations and closing roads when there is a risk of flooding. A voluntary or mandatory evacuation order is sometimes issued if the risk to life is high. With sufficient advance warning it may also be possible to reduce the extent of flooding; for example, by raising temporary flood defences, clearing watercourses of debris, reducing reservoir levels, and operating flood control gates and barriers. At a smaller scale, sandbags, flood boards and other measures are widely used to protect individual properties.

Typically many different agencies are involved in this type of response. For a warning system to be effective, roles and responsibilities therefore need to be clearly

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defined and flood response plans kept up to date. The performance of the system also needs to be monitored and regular reviews performed, particularly after major flood events. Where improvements are required, if any significant investment is required then this often needs to be justified using cost-benefit, multi-criteria or related techniques.

Taken together, these various activities fall under the general heading of ‘preparedness’ and – as discussed in Chap. 1 – this is one of the key components in an integrated, end-to-end or total flood warning system. For example, in the USA, as part of the National Incident Management System, preparedness is considered to cover a continuous cycle of planning, organizing, training, equipping, exercising, evaluating, and taking corrective action (http://www.fema.gov/). Similarly, UN/ISDR (2006a) notes that for early warning systems in general there are four key elements to consider:

- 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?
- 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?

For fast developing hazards such as flash floods, the response capability is particularly important and, as discussed in Chap. 1, a community-based or people-centred approach is widely advocated. This does however require active collaboration between all parties; for example, NOAA/NWS (2010) notes that local, community-based flood warning systems "…..require a high level of ongoing commitment and support beyond one-time installation costs. Those with the most success have proactive, energetic staff members; strong long term operational funding; and a good rapport with the local NWS (*National Weather Service*) forecast office." Similarly, regarding community-engagement, the Australian national guidelines (Australian Government 2009a) note that "the critical issues in developing and maintaining 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"

Table 7.1 Some examples of national and international guidelines on warning systems

Topic	Location	Reference
Rivers	USA	US Army Corps of Engineers (USACE 1996)
		Federal Emergency Management Agency (FEMA 2006)
		NOAA/National Weather Service (NOAA/NWS 2010)
	Australia	Australian Government (2009a, b)
	International	World Meteorological Organisation (2008, 2011)
		National Oceanic and Atmospheric Administration (NOAA 2010)
		WMO/GWP Associated Programme on Flood Management (APFM 2007, 2011a, 2012)
Debris flows	International	WMO/GWP Associated Programme on Flood Management (APFM 2011b)
Urban flooding	International	United Nations Educational, Scientific and Cultural Organisation (UNESCO 2001)
		WMO/GWP Associated Programme on Flood Management (APFM 2008)
Dam breaks	USA	Federal Emergency Management Agency (FEMA 2004)
	Australia	Australian Government (2009c)
Severe weather warnings	International	World Meteorological Organisation (2010)
All-hazards	UK	Cabinet Office (2012)

To help to meet these objectives, in some countries, the nature of the warning service offered has been formalized by establishing service level agreements and introducing performance targets; for example, for the numbers of people covered and the minimum warning lead times to be provided (where this is technically feasible).

This chapter provides an introduction to these various topics. The areas covered include flood response planning, post-event reviews, performance monitoring, emergency response exercises, and the development of improvement plans. The general approaches used for flood risk assessment are also discussed, whilst specific techniques for different types of flash flood are described in Chaps. 8–11. Further information on these topics is provided in the many guidelines and manuals available on developing early warning systems, including the examples summarized in Table 7.1. Several other national and international examples are cited in later chapters for specific types of flash floods.

7.2 Flood Risk Assessment

7.2.1 General Approach

As in other aspects of flood risk management, for flash flood warning systems a key task in planning is to understand and quantify the risk to people and property. This then allows effort to be targeted at the groups and locations that are most at risk. Table 7.2

Table 7.2 Some examples of the types of information potentially of use in flood risk assessment studies

Source	Description
Anecdotal evidence	Information obtained from interviews with residents, local authorities and others with long experience of flooding issues in an area
Field surveys	Site visits to assess potential flooding mechanisms, areas at risk, and any topographic or river channel survey required to support flood modeling studies
Flood modelling	Statistical, hydrological and hydraulic modeling studies based on historical observations for flows and other variables
Geomorphological studies	Evidence from ground survey of alluvial deposits and from aerial and satellite images, including paleoflood evidence
Historical evidence	Information gathered from newspaper and photographic archives, websites, national flood chronologies, research papers and other sources, such as commemorative flood markers in towns and cities
Post-event survey	Systematic surveys of the flood extent and the damages following major flood events, including 'witness' marks such as trash and debris along river banks and the flood levels reached on buildings
Remote sensing	Satellite images and/or aerial photographs of flood extents captured during previous flood events, including media footage (if available) and satellite-based soil moisture estimates
Road and rail flood studies	Previous flood-related analyses and risk assessments for roads and railways, such as from culvert and bridge design studies

summarises some of the main sources of information which are used in assessments of this type, whilst some general guidelines on this topic include examples published for Japan (MLIT 2005) and Europe (EXCIMAP 2007; Meyer et al. 2011).

When combined with expert judgement, these approaches help to build up an overall assessment of the causes of flooding and the flood risk. The extent to which each method is used typically depends on budgets, the level of risk and the information which is available. Assessments of potential climate change impacts are also increasingly included using sensitivity studies or downscaled scenarios from general circulation models.

As might be expected, no single method provides a complete picture. For example, although satellite images often provide an excellent indication of the spatial extent of flooding, these might not have been taken at the peak of the event or have sufficient resolution for some events. By contrast, for aerial surveys, although the resolution is higher, sometimes it is only possible to overfly the area once weather conditions improve. For geomorphology studies, although these can show evidence of extreme events in the past, the conclusions might no longer be relevant to current catchment conditions due to land use and river channel changes and recent engineering works such as levees and reservoirs.

In contrast, post-event and field surveys normally provide more up-to-date information, although typically resources only allow a limited number of locations to be visited, with a bias towards the areas most affected (or newsworthy). This inherent subjectivity is even more of a factor when considering anecdotal evidence; for example, people who have been affected by flooding sometimes make no distinction between river and surface water flooding, and newcomers to an area may have little knowledge of larger flood events in the past. By contrast, newspaper or other accounts from decades ago often show that the flood risk is much higher than expected based on recent experience alone, although again catchment conditions could have changed since that time.

Flood modeling techniques also have some limitations – particularly the more empirical approaches often used for road and rail studies - but are increasingly used in many countries. A key advantage is the ability to provide a quantitative assessment of risk, linked to the probability of occurrence and the consequences of flooding. However, other methods still have a valuable role to play in calibrating and validating models and for initial flood risk assessments. Usually, another important step is to discuss and review the outputs from the analyses with local experts, community members and others with an interest in the results.

The modelling techniques which are used depend on the type of flash flooding, and Chaps. 8–11 discuss the approaches used for river flooding, ice jams, debris flows, surface water flooding, dam breaks, levee breaches and glacial lake outburst floods. The results are often presented as flood risk maps and Geographic Information Systems (GIS) are widely used in these types of analyses, supported by high resolution digital terrain models. Maps for combined sources of flooding are sometimes also produced; for example considering the risk from both rivers and surface water flooding in urban areas. In some countries, the resulting maps are published on websites as part of national flood risk mapping programmes as new areas are mapped and improvements are made to existing coverages; for example, in England and Wales these are updated on a 3-monthly cycle (http://www.environment-agency.gov.uk/).

7.2.2 Flooding Impacts

Flood risk is normally defined as a function of the probability and consequences of flooding, where the consequences are expressed in terms of impacts such as the number of properties flooded or the economic damages.

As noted in the previous section, estimates for the probability are typically obtained from flood modelling studies or alternatively, where this is not possible, by assigning indicative values, such as ‘high’, ‘medium’ or ‘low’. Increasingly, the consequences are considered in terms of two quantities: the exposure and the vulnerability. Here, the exposure is a measure of the physical risk from flooding whilst the vulnerability expresses the social, economic and environmental impacts on individual groups in society. In flash flooding incidents, some factors which potentially increase the vulnerability of groups or individuals include:

- the types of buildings at risk; in particular single-storey buildings, mobile homes and temporary or semi-permanent structures

- underground locations at risk, such as car parks, underpasses and basements
- people in vehicles either attempting to drive through floodwater or caught unexpectedly by flooding (e.g. at night)

However, socioeconomic status is also often a factor although the groups or individuals considered can vary widely between countries. For example, in an Australian context, some groups who may be considered especially susceptible to the hazards floods pose include the elderly, the poor, single-parent families, large families or families with very young children, those lacking access to a motor vehicle, newcomers, members of culturally and linguistically diverse communities, the ill or infirm, and those whose homes are isolated by floods (Australian Government 2009b).

Of course, much depends on the circumstances for each individual or family. For example, for a given depth and extent of flooding, housebound elderly people are usually more vulnerable than their able-bodied counterparts who can simply walk to safety. Indeed, the likely flood durations and velocities are particularly important to consider for flash floods, and in some cases are produced as outputs from flood models, in addition to estimates of flood depths. For example, high velocities often increase the risk to vehicles, pedestrians and structures such as mobile homes and caravans. The risks from debris are sometimes considered as well, although usually in a qualitative way; for example to indicate the potential risk from blockages at bridges and other structures.

In some cases it is useful to combine risk indicators into an overall score by adding or multiplying a set of individual factors. Typically, the results are presented as maps overlain on key features of interest, such as properties, community facilities, and critical infrastructure (e.g. Meyer et al. 2009). As discussed later, maps of this type are useful in emergency planning, prioritizing investment and a range of other applications.

In flood warning applications, another consideration is the extent to which critical infrastructure is at risk. For example, ASFPM (2011) suggests that critical facilities fall within the following categories:

- Governmental Facilities: Essential for the delivery of critical services and crisis management, including data and communication centers, key government complexes, etc.
- Essential Facilities: Those that are vital to health and welfare of entire populations, including hospitals and other medical facilities, retirement homes, police and fire departments, emergency operations centers, prisons, evacuation shelters, and schools, etc.
- Transportation Systems: Those systems, and the supporting infrastructure, necessary for transport of people and resources (including airports, highways, railways, and waterways) during major disasters, including flood events up to the 500-year flood.
- Lifeline Utility Systems: Those vital to public health and safety, including potable water, wastewater, oil, natural gas, electric power, communication systems, etc.

Table 7.3 Illustration of some typical steps in producing flood warning and evacuation maps

Item	Examples of steps required
Flood warning zones	Adjusting and dividing up the flood risk boundaries (envelopes) to show the operational zones for which warnings are to be issued and the numbers of properties and people at risk in each area
Hazardous materials	Identifying locations which – if flooded – would present a hazard both to staff and to the wider community, such as chemical works, sewage treatment works, factories and oil refineries
High-risk locations	Highlighting the locations of critical infrastructure at risk, bridges which are potentially vulnerable to flood or debris damage, and flood defence assets which could require inspecting, operating or reinforcing, such as levees and flood control gates
Operational response	Annotating maps with operationally useful information such as warning dissemination techniques, likely flood paths and depths, river gauge locations, threshold levels for flood warnings, shelter locations, meeting points, evacuation and escape routes, key contact numbers, websites for weather, flood warning and other information, and the locations of sources/stockpiles of equipment, water, food and medicine (as appropriate)
Vulnerable groups	Highlighting the locations of vulnerable groups such as individual householders and schools, care homes, prisons, hospitals, and isolated rural properties

- High Potential Loss Facilities: Failure or disruption of operations may have significant physical, social, environmental, and/or economic impact to neighboring communities, including nuclear power plants, high-hazard dams, urban levees, and military installations.
- Hazardous Material Facilities: Involved in the production, storage, and/or transport of corrosives, explosives, flammable materials, radioactive materials, toxins, etc.

Information on the risk to these types of facilities is useful both for long-term planning of measures to protect sites from flooding, and for developing response plans summarising the actions to take during a flood event if a site is threatened by flooding. For example, as discussed in Sect. 7.4, in addition to disruption at the site itself, there can be severe consequential impacts, such as contamination of drinking water and the temporary loss of phone and electricity networks and water supplies.

7.2.3 Flood Warning and Evacuation Maps

For flood warning applications, once the flood risk has been assessed (by whatever means) an additional step is normally required to translate the results into operationally useful tools (e.g. Osti et al. 2009; Meyer et al. 2011). This is best performed in collaboration with key partners in the flood warning process such as emergency responders, civil protection agencies and community representatives. Again, a map-based approach is widely used and Table 7.3 illustrates some typical steps required to produce flood warning and evacuation maps. Figure 7.1 also contrasts some of

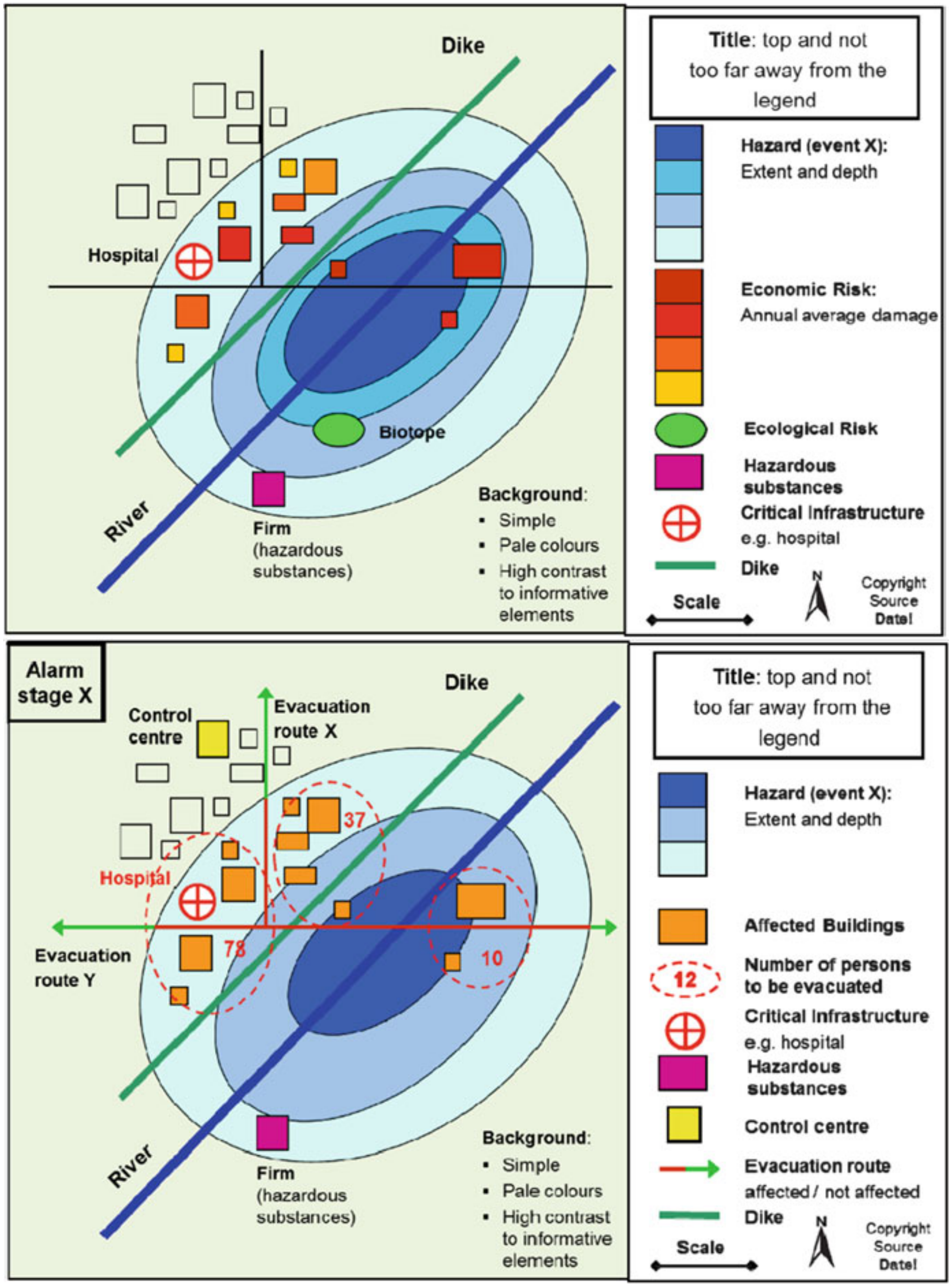

Fig. 7.1 Idealised maps developed as part of a European research study into best practice in flood risk mapping, illustrating the different requirements for strategic mapping (*top*) and emergency management (*lower*) (Adapted from Meyer et al. 2011)

the differences between maps used for assessing flood risk (strategic planning) and for emergency management.

The information that is provided varies widely between different users but generally it is important to show this in terms which are meaningful at a community level; for example to relate river gauge levels to likely flood extents and to use zones or sub-areas which follow community boundaries and naming conventions, such as for districts and suburbs in a town. In many cases it is useful to generate a series of maps corresponding to different river levels or flood stages. In addition, databases of property addresses and contact details are sometimes generated for use in multimedia and other automated flood warning dissemination systems (see Chap. 6).

For operational use, another consideration is whether maps should be paper-based or electronic. For example, if paper-based maps are used, they remain accessible even if there are power or telecommunications failures, and to people without computer or smartphone access. However digital maps provide more functionality, including pan, zoom and overlay facilities and the option to quickly select the map(s) appropriate to different gauge levels or forecasts. The internet has also greatly facilitated the sharing of maps and other operationally useful information during flood events. For example, Box 1.1 describes a flood map viewing application developed by a river basin management authority in the USA and Chap. 6 discusses real-time decision support systems for use during flood events.

A logical next step beyond using pre-defined maps is to estimate the inundation extent dynamically using real-time hydraulic models and then to overlay this on the information required for the emergency response. To date, the forecasting tools required are only available for some types of flooding, such as for river and surface water floods but this approach has the potential to accommodate event-specific factors as they occur, such as tidal influences and unexpectedly high inflows from key tributaries. However, the use of models in this way tends to be limited to situations where there is high confidence in the model outputs. As discussed in Chaps. 8 and 10, this is in part due to the computational power required but also because, for operational use, there is rarely enough time to carefully check and audit the model outputs as is normally done for off-line modelling studies.

7.3 Flood Response Plans

7.3.1 Introduction

During a flood event, and in particular a flash flood, there is usually little time to find key information or take warning decisions, and a risk that vital actions could be overlooked. Many civil protection and emergency management authorities therefore document the actions to take by producing flood response plans, and work with other groups to ensure that roles and responsibilities are clearly understood. Alternative names include flood incident plans, flood emergency plans, intervention plans and flood emergency management plans.

The use of procedures also helps to provide a more consistent and less subjective approach to decision-making, particularly for new staff and people co-opted to assist during emergencies. The discussions required to formulate a plan also help to foster collaboration between individuals in different organisations and key community members, and these personal links are often an important factor under the pressure of a flood event. Another valuable role is in retaining 'corporate memory' as key staff leave or retire and others take their place.

Flood response plans are typically produced at a number of levels including household and community plans, and also include the flood warning procedures for use by flood warning staff (see Chap. 6). In some cases these are stand-alone documents whilst in others they form part of multi-agency and/or multi-hazard plans. Organisations which typically have plans in place include local authorities, emergency responders (police, fire, ambulance etc.), utilities, businesses, health and welfare organisations, and operators of any critical infrastructure at risk. Sometimes, particularly in the private sector, flood response plans form part of so-called contingency or business continuity plans.

The level of detail included needs to be tailored to each situation, and some examples of actions which may need to be taken in the run up to and during a flood event include (USACE 1996):

- providing search, rescue, and evacuation services
- scheduling closure of schools and transportation of students
- curtailing electric and gas service to prevent fire and explosions
- establishing traffic controls to facilitate evacuation and prevent inadvertent travel into hazardous areas
- dispersing fire and rescue services for continued protection
- establishing emergency medical services and shelters
- closing levee openings
- moving public and private vehicles and equipment from areas subject to flooding
- relocating or stacking contents of private structures
- initiating flood-fighting efforts, and
- establishing security to prevent looting

A common feature throughout is generally an emphasis on 'buy-in' and endorsement by the agencies and communities involved. Clear statements are also needed on the criteria for activating a plan, such as a heavy rainfall warning, a flash flood alert, or reports of flooding from staff and the public. Also, the need for a process of continuous assessment is often highlighted to keep plans up-to-date and validated, and plans increasingly fall within the scope of the quality management frameworks operated by many organisations. For example, some criteria for evaluating or vetting a plan could include consideration of whether it adequately covers the following topics (Australian Government 2009b): Authority, Ownership, Objectives, Scope, Flexibility, Scale, Completeness, Users, Agencies' Needs and Responsibilities, Physical Description, Hazard Analysis, Community Analysis, Lifelines, Activation, Management, Review, Standing Operating Procedures (SOPs), Document Management. As another example, as part of a European study, 22 metrics were identified in the general areas of objectives, assumptions and target audience, organization and responsibility, communication, flood hazard, flood risk to receptors (e.g. people, buildings, critical infrastructure) and evacuation (Lumbroso et al. 2012).

Some other general principles are that plans should be sufficiently flexible (or resilient) to cope with changes as an event develops, and provide a clear chain of command, particularly for interactions with the public and the media. Mutual aid arrangements for national and international assistance are usually also included in case of large-scale events, and contingency arrangements in case of problems with equipment, communications, power supplies and other eventualities. For example, ASFPM (2011) suggests that the following questions can assist with determining if a facility is critical:

- If flooded, would the facility add another dimension to the disaster? (e.g. petroleum terminals, hazardous and toxic waste sites)
- Based on the available flood warning time, would people be able to evacuate the facility/building without loss of life?
- Would the facility be operable during an extreme flood event (e.g. 500-year flood)?
- Would essential and irreplaceable records, utilities, and/or emergency services be lost or become inoperable?
- If the services provided by the facility were disrupted by flood (e.g. police, fire, emergency services), would the flood disaster result in even more damages and loss of life?

As indicated, there is a need to consider what would happen if a flood event turns out to be more extreme than experienced in the past. Also, health and safety issues are often a particular consideration since flood waters may present medical, fire and electrocution risks, as well as the risk of drowning. For example, common contaminants include fuel, oil, sewerage, animal carcasses and industrial chemicals, with a risk of waterborne diseases following the event.

In some cases, such as for a major city or regional warning system, plans are lengthy documents. However, in recent years, the availability of the internet and other computer tools has transformed how they can be delivered and shared. For example, this helps with keeping plans up to date to take account of changes in staff, flood warning arrangements, organizational structures, flood protection measures, equipment and other factors. Also, as discussed in Chap. 6, the facility to dynamically generate and update plans as an event develops is increasingly used as part of decision support systems. However backup arrangements – such as paper-based copies - are still normally required in case of power, communications or other failures during a flood event.

7.3.2 Community Response Plans

Community response plans are at the centre of many flood warning systems. Again, formats vary widely and the amount of detail often depends on the level of flood risk and the complexity of the system(s) under consideration.

Some typical items which are included are the criteria (thresholds) for initiating the plan, the roles and responsibilities for each group, arrangements for assisting vulnerable groups, flood fighting actions which are likely to be needed, and health and safety issues. In some cases this requires considerable detail for some topics; for example, regarding arrangements for using sandbags to protect or raise a flood defence (dike or levee) some tasks required could include (Flood Control District of Maricopa County 1997):

- Notify the designated responsible party
- Pick up the sandbags
- Deliver the bags to the sand source
- Fill the bags
- Deliver the bags to the dike

Also, some useful questions to address could include "Who performs these individual tasks? Where are the bags stored and where is sand available? Are there volunteer organizations (e.g. homeowners association, block watch groups) on-call to assist in the labor-intensive task of filling sandbags?"

In many cases there is a need to consider different sets of actions depending on the times at which warnings are received and flooding is anticipated; for example, during or outside normal business hours, in summer or winter, or by day or night. Some plans also extend into the routine actions required to improve preparedness for flooding, such as stockpiling of supplies, food and medicine, flood proofing of properties, public awareness campaigns, and training exercises. Where communities operate their own flood warning systems, detailed operating instructions are typically included for each sub-system (see Chap. 6). More detailed sections are sometimes also included for issues such as casualty treatment, maintenance of vital services, and controlled shutdown or protection of sites with hazardous material.

In some countries, the development of community-based plans is encouraged through insurance-related or other incentives. For example, in the USA, flood preparedness is one of the criteria by which communities in flood prone areas can qualify for a discount on premiums under the National Flood Insurance Program. The five qualifying elements are flood threat recognition, emergency warning dissemination, other response efforts – such as defining warning thresholds and developing plans for flood fighting, critical facilities planning, and being 'StormReady' (FEMA 2006). Here, the StormReady Program has been designed specifically to help communities to become better prepared for storms and other natural hazards, such as floods. Accreditation includes the requirement to develop a response plan, establish methods to gather data and disseminate warnings, and various community preparedness activities. There is also a requirement to establish a 24-h warning point and – for larger communities – an emergency operations center http://www.stormready.noaa.gov.

Household response plans often form another component of community-level plans. Typically these are issued in the form of short leaflets or posters and on websites, and provide advice on issues such as:

- Sources of information on flood risk (e.g. flood maps, contact details),
- Flood warning arrangements (e.g. flood warning codes, website addresses)

- Evacuation arrangements (e.g. safe routes, shelter locations),
- Items to take on evacuation (e.g. flashlight, first aid kit, cellphone)
- Actions to take to reduce flood damage (e.g. raising furniture and electrical items to higher levels, use of sandbags)
- Actions to take to protect valuables and memorabilia (e.g. keep copies elsewhere, take photographs of key items)

Specific advice is sometimes also provided for drivers on the risks in trying to drive through flash floods, and this topic is discussed further in Chap. 12. In less developed economies and rural areas, advice is often included on safeguarding livestock and cooking and farming tools, and on stockpiling food, fuel, water and fodder.

More generally, some activities which are used by warning system operators to maintain awareness of flooding include community meetings, flood fairs and school outreach programmes. Emergency response exercises also play an important role, as discussed in Sect. 7.6. Other examples include writing newspaper articles on the risks from flooding and producing radio and television programmes on similar topics. In some countries there is also a tradition of storytelling via plays and dramas to raise flood awareness. For example, in a review of warning procedures for debris flow and landslide disasters in Japan (MLIT 2007), one municipal head suggested that “It is our wish to integrate disaster-related traditions, life stories, folktales, records of past disasters, stories told by old people, etc. and hand them down to posterity”. Some organizations have also developed websites providing advice in the form of videos, three-dimensional visualizations, audio messages and other approaches; one innovative example being for the city of Boulder in Colorado which has one of the highest flash flood risks in the USA (http://www.boulderfloods.org/).

7.3.3 Evacuation Plans

In some cases, community and other response plans include a discussion of evacuation procedures. Where these are required they merit particular attention since this is a complex area with many factors to consider.

For flash floods, due to the limited time available, typically there is a difficult balance to draw between unnecessary evacuations (false alarms) and leaving it too late to evacuate all people safely. This requires an understanding of the various time constraints and critical decisions which need to be made. For example, Fig. 7.2 provides an illustration of the various phases into which an evacuation can be divided. More generally, there is often a trade-off between the risks of evacuation and the risks of leaving people in place. For example “hazards that evacuees may be exposed to whilst evacuating include flooding of evacuation routes, severe weather including strong winds, heavy rainfall, hail and lightning, debris, and fallen electricity lines” (Australian Government 2009b).In addition there may be health-related risks in moving vulnerable groups such as hospital patients and nursing home residents

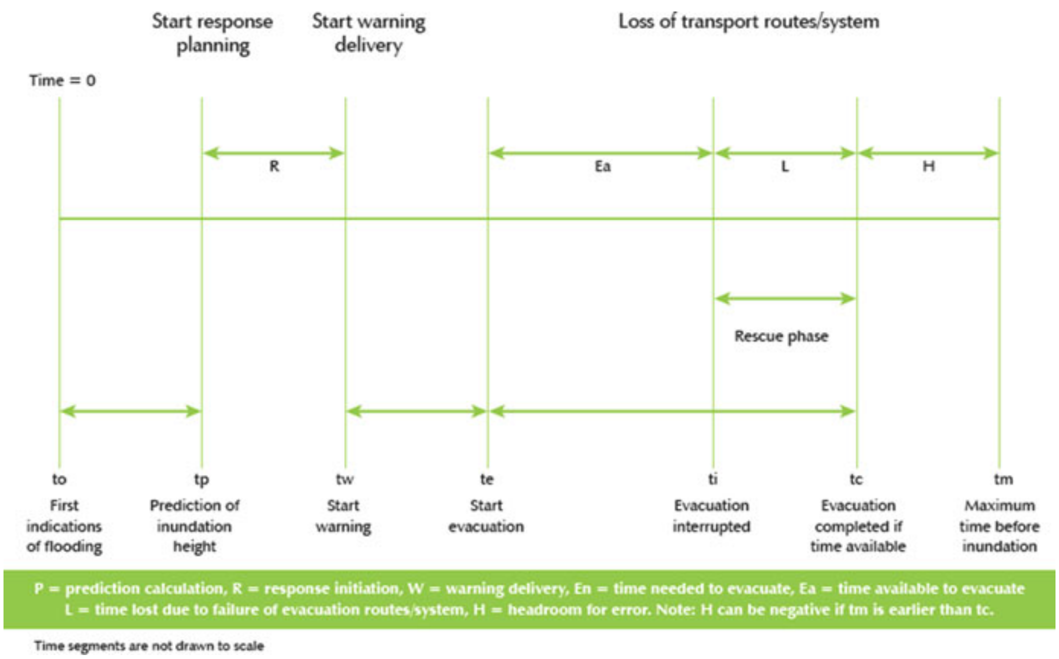

Fig. 7.2 An evacuation timeline (Australian Government 2009b). (Reproduced with the kind permission of the Australian Government Attorney-General's Department)

Another question to consider is whether an evacuation should be voluntary, recommended or mandatory and – in the latter case – how that should be enforced? Different countries take different approaches and a mandatory evacuation often requires assistance from the police as well as civil protection staff. However, for flash flood events, due to the short time available, it can be more of a challenge to assist large numbers of people to move compared to riverine events. There is also less time for a personal approach to informing people, such as phone calls or door-knocking. Despite these difficulties, though, there have been many cases where even with a short lead time successful actions have been taken to reduce risk to life.

Due in part to the large volume of research on the response to hurricane and tropical cyclone warnings, there are many tools and procedures available to assist with evacuation planning (see Wolshon et al. 2005 for example). In the USA, for example, the planning process typically requires a hazard analysis, a vulnerability analysis, an evacuee behavioural analysis, a sheltering analysis, and a transportation analysis (e.g. USACE 1995). Evacuation plans are normally also a key part of the response planning process for dam break emergencies (see Chap. 11) and evacuation management tools are increasingly included in real-time decision support systems (see Chap. 6).

7.4 Post-event Reviews

Following major flood events, many organisations produce post-event reports. Some other names which are used include service assessments, post-flood reviews, evaluation reports and lessons-learned reports. Two high profile examples were the reviews following Hurricane Katrina in 2005 (US House of Representatives 2006) and the Indian Ocean Tsunami in 2004 (e.g. UN/ISDR 2006b). Some organisations also routinely publish preliminary findings within days of a flood event occurring.

Generally the main requirement is to examine the performance of all aspects of the flood warning process and response, including technical, organisational, procedural and social issues. This can help with identifying areas for improvement and is sometimes formally required as part of a service level agreement or during an independent enquiry. As for flood response plans, the formats used vary widely, but Table 7.4 illustrates some of the topics which are typically included.

Depending on the scale of the event and resources available, it is often useful to perform detailed site surveys and hold consultation meetings with residents to provide additional information to inform the analyses. For example, some questions on the content and delivery of messages that might be posed include (Australian Government 2009a):

- Did the target audience receive the warnings in time?
- Did they understand the warning messages?
- Were their responses appropriate? If not, why not?
- What evidence is there for the answers to these questions?

Of course, great care is needed not to interfere with the rescue and recovery effort with sensitivity to the distress and possible anger of those affected by flooding. Many countries and international agencies also have well-defined procedures for collecting information immediately after disasters to inform the response and recovery effort and some tasks relevant to post-event reporting include:

- Data recovery – downloading of observations and forecasts for subsequent analysis, such as raingauge, river gauge, CCTV, satellite, weather radar, Numerical Weather Prediction model and nowcasting outputs and satellite imagery (if not already systematically archived for future use)
- Debriefing – of community volunteers, emergency response and other key staff involved in the flood response to record what they observed, their assessment of the response and ideas for improvements
- Film evidence – collection of videos and photographs from the media, the public, the emergency services (e.g. from helicopters) and others, and from staff members and subcontractors sent on site during or immediately after the event
- Flood extent – surveys of trash marks and debris left at the peak of the flood, and of any flood markers placed by staff and others, in some cases supported by hydraulic modelling (see Chap. 3) to estimate the peak flows at key locations
- Social research – structured interviews, meetings and questionnaires to discuss the views of the community, businesses, infrastructure operators and others on the flood response (including flood warnings) and to elicit key information such as the warning lead times provided, damage caused and the time sequence of rainfall and flood events

In some cases, these tasks build on the flood data collection activities described in Box 6.2 which are performed as a flood occurs, for which some examples include high flow gaugings and placing temporary flood markers at high water marks.

Table 7.4 Some examples of the topics typically included in flash flood post-event reports

Topic	Description
Asset performance	Analyses of the performance of flood defences (levees), flood control structures and other assets, including any emergency repairs made, performance issues and recommended remedial actions
Damage avoided	Analyses of the damages avoided through issuing flood warnings and from the protection provided by flood defences (levees) and other flood risk mitigation measures, both in economic terms and using other measures, such as the number of properties for which flooding was avoided
Flood losses	Inventories of the social, economic and business losses and disruption during and following the event, with more detailed accounts of the circumstances leading to any loss of life or impacts on critical infrastructure such as electricity, gas or water supplies, and telecommunications
Flood warning performance	Feedback from community members, the emergency services and others on the warnings received and how useful they were, including the lead times provided, understanding of messages, and the actions taken, and more formal performance measures of the types discussed in Sect. 7.5
Hydrometeorological analyses	Descriptions of the synoptic conditions leading to the flood event, the magnitude and distribution of rainfall, the flood levels reached and hydrological response, and estimates for the return period or annual exceedance probability of the event
Interagency coordination	Discussions of how well (or not) organisations collaborated, and recommendations for improvements to procedures, telecommunications, equipment etc., including any issues regarding interoperability of equipment, interactions with the public and the media, and with staff availability and deployment
Monitoring and forecasting	Analyses of the performance of rainfall and flood forecasting systems, including the accuracy of forecasts and the lead times provided, and of the performance of observation and telemetry systems, including any flood data collection activities performed (see Box 6.2) and issues with telemetry failure or flooding at gauge locations
Response and recovery	A summary of the emergency response actions taken (evacuations, rescues, flood fighting etc.) and accounts of (or plans for) recovery from the flood event
Timelines	A description and possibly charts to illustrate the sequence of events including times for the onset of flooding, warnings issued, key flood fighting actions, rescues and other significant items
Thresholds	A review of the decision criteria used for issuing warnings, and recommendations on possible adjustments to reduce false alarm rates or increase detection rates and lead times in future

For the hydrometeorological component in post-event reports, the tools which are available nowadays potentially allow for much more detailed investigations than was possible even a few years ago. For example, many countries now operate weather radar networks and Numerical Weather Prediction and nowcasting models. The archived outputs can therefore be analysed for the time leading up to and during the event, and model runs repeated if useful at a higher resolution or using observations which were not available in real-time at the time of the event. The resulting estimates are sometimes then used as inputs to rainfall-runoff and hydraulic models to assess the runoff dynamics and estimate the peak flows reached at sites without suitable instrumentation (e.g. ungauged locations). More traditional techniques still have a valuable role to play though, such as collecting rainfall amounts recorded at manually operated raingauges and making use of anecdotal evidence from the public and others. Circumstantial evidence, such as the depth of water in buckets and discarded containers, sometimes also helps to build up a picture of the extent and severity of rainfall.

Where meteorological and hydrological functions are separated by organization it is useful to have agreements in place for routinely performing these types of studies after major events. Suggested procedures have also been developed for some situations, such as for flash floods on rivers (e.g. Gaume and Borga 2008) and debris flows (e.g. Hübl et al. 2002). More generally, one of the main outcomes from a post-event review is normally an action plan to address any aspects of performance which could be improved in advance of the next major flood event. For example, Table 7.5 illustrates some of the technical and communications issues which often appear in post event reports and provides examples of the types of options for improvement which are sometimes suggested, depending on the particular problems faced by the organisations involved. Usually there are a number of social response factors to consider as well and Chaps. 6 and 12 discuss this topic further.

7.5 Performance Monitoring

Flood warning performance measures are widely used to assess whether a system is meeting requirements and to help to identify any changes over time (e.g. Handmer et al. 2001; Elliott et al. 2003; Andryszewski et al. 2005; Basher 2006; FEMA 2006). In some cases they are also included as targets in level of service agreements (e.g. Andryszewski et al. 2005) and/or used in developing long-term flood warning and forecasting investment plans and strategies (see Box 7.2). The choice of factors to consider is best determined as a collaborative exercise between all key stakeholders in the flood warning process taking account of different views on the requirements of a flood warning service. The costs and feasibility of collecting the information required also need to be considered, both on a regular basis and following flood events.

Table 7.5 Illustration of some of the technical and communications difficulties and proposed long-term solutions which often appear in post-event reports (Adapted from Sene 2008)

Topic	Issue	Some possible options
Access routes	Access to locations likely to flood affected by flood waters or the weight of traffic	Pre-position key staff, vehicles, and equipment, prioritise flood fighting and rescue actions before access routes are cut off
Control centres	Communications, power or access issues, or the site itself affected by flood water. Inability to handle the level of media and other requests for information	Set up a backup location in areas away from flooding, with permanent relocation if the flood risk is significant. Increased staff levels and training
Equipment shortages	Limited availability of communications, flood fighting, medical and rescue equipment, problems with accessing information on the resources available	Develop regional inventories and mutual aid arrangements, stockpiling of equipment at strategic locations, use of real-time decision support systems
Evacuation	Roads blocked by floodwater or the weight of traffic; fuel inaccessible or in short supply; lack of information or procedures for requisitioning transport; insufficient record-keeping on areas evacuated	Develop and test evacuation plans, possibly assisted by computer modelling of scenarios. Explore options to use boats, helicopters, hovercraft, amphibious vehicles etc.
Flood warning	Key telecommunications routes and hubs affected, blocked access for door-knocking or loud hailer routes, television and radio broadcasts interrupted, overloading of websites, call centres and phone systems, out-of-date contact lists	Use multiple dissemination routes, both direct and indirect, flood proof key installations, load test for high call volumes during emergency response exercises, keep simple backup methods in reserve e.g. hand-held radios (see Chap. 6)
Hazardous materials	Flood waters affect sewage treatment works and contain fuel, chemicals, human waste and other toxins	Procure protective equipment for staff (dry suits etc.), develop standard decontamination procedures, advise the public, media and others on the risks
Inter-agency cooperation	Systems prove to be incompatible, uncertainties about how or when to escalate the response or request additional or external assistance (e.g. military, coastguard), overly rigid or bureaucratic procedures causing delays, poor signal strength on site for cell, radio etc.	Investigate the frequencies and coverage for systems used by other organisations, particularly for radio communications. Establish criteria/triggers for escalating the response. Streamline decision-making processes delegating authority to lower levels where appropriate. Develop shared decision support tools

(continued)

Table 7.5 (continued)

Topic	Issue	Some possible options
Monitoring, forecasting	Failure of key instruments or telemetry links, forecasts prove to be inaccurate, no facility to forecast event-specific problems (e.g. dam breaks), hydrodynamic model runs fail to complete or take too long to provide useful results	Use dual-path telemetry links and/or backup power supplies, increase use of voluntary observers, improve model performance and functionality, maintain simple forecasting models as a backup, consider backup instruments at high risk locations, raise key electrical equipment above likely peak water levels and increase recording range
Shelters	Some sites flooded or inaccessible to evacuees and staff and vehicles bringing food, water and clothing	Choose locations for rescue centres away from flood waters and with good access even in flooding conditions
Staff welfare	Possible issues from waterborne diseases, hazardous materials, hours on duty, friends and family affected by flooding	Review training, equipment, duty rosters, protective equipment, support and counseling arrangements etc.
Utilities	Flooding interrupts power, water and gas supplies, in some cases with consequences for areas not affected by flooding	Have backup supply arrangements planned as far as possible, and alternatives such as bottled water, clothing etc.

The types of measures which are used have many similarities to those for assessing the performance of meteorological and flood forecasting models, and which are discussed in Chaps. 4 and 5. However, one key difference is that they normally include social and other factors which are outside the control of any one organization. For example, some key performance indicators may include 'such things as prediction accuracy and timeliness, the percentage of those who were intended to evacuate who actually did so, and evidence of community acceptance and comprehension of the warnings that were disseminated' (Australian Government 2009a).

Table 7.6 shows some examples of the types of measures which are used (e.g. CNS Scientific and Engineering Services 1991; Carsell et al. 2004; Parker 2003). However the precise definitions differ widely between organisations and sometimes change over time, so these examples are for illustration only. In some cases, it is also more practical to consider individual households or street addresses, rather than the numbers of people affected. Similarly, another choice is whether to define measures in terms of the number of flooded properties in receipt of a flood warning service, or the total number flooded.

Values are typically estimated based on feedback from the individuals affected, examination of incident and communications logs, and post-event social surveys.

Table 7.6 Some illustrative examples of flood warning performance measures

Measure	Description
Ability to respond	The proportion of people able to act upon a warning and not hindered in some way; for example due to language difficulties or disability
Availability to respond	The proportion of people who received a warning which was sent to them (and were not away from their normal residence, for example)
Effectiveness of response	The proportion of people who received a warning and subsequently took appropriate actions
False alarms	The proportion of people who received a warning who were not subsequently affected by flooding
Warning lead time	The lead time provided before the onset of flooding

Regular (e.g. annual) user satisfaction surveys are also performed by some organisations based on a sample of the residents in receipt of a flood warning service. Other more general measures are sometimes used relating to factors such as the level of public awareness and overall preparedness, number of emergency response exercises performed, and availability of flood response plans. For example some possible general headings considered in one research study included preparedness, forecasting, warning and promoting response, other communication, coordination, media management, equipment provision, environmental damage, economic damage, injuries, loss of life, victim trauma and reputation (Environment Agency 2007).

However, it is probably fair to say that, amongst flood warning services which have formally adopted performance measures, initial results from the first few surveys have often been disappointing, although have improved over time. For example "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" (Flood Control District of Maricopa County 1997). One value of this decomposition of the warning process is therefore that it helps to understand the individual social, technical and other factors which limit performance.

A key task then is to understand the reasons for any shortcomings through more detailed analyses, social research, and comparisons with other organizations. For example, in a review of the flood warning systems in several European countries (Parker et al. 1994) the measures that were considered included attitudes to freedom of risk/hazard information, public education about warnings, dissemination of lessons learned, performance targets and monitoring, and national standards and organisational culture. Studies into the human factors which affect performance also have a valuable role to play although it is worth noting that the process of interviewing and collating information can be a major undertaking, even for a sample size of just a few tens to hundreds of people. Some other possibilities for interpreting findings include analytical approaches such as root-cause, event-tree, agent-based and failure mode analyses (e.g. Environment Agency 2009).

To evaluate changes in performance over time, it is often convenient to aggregate values over a number of flood events and locations. For example, some measures which are used include:

- Coverage (C) – the proportion of people at risk from flooding who are in receipt of a flood warning service
- False Alarm Ratio (FAR) – the proportion of flood warnings issued for which no flooding occurred (sometimes called the False Alarm Rate)
- Probability of Detection (POD) – the proportion of flooding incidents for which an accurate and timely flood warning was provided
- Warning lead time – the minimum, average or median lead time provided before the onset of flooding

Although the precise definitions vary between organisations, POD and FAR values are typically calculated using a contingency table approach, as illustrated in Chap. 5 for the performance of flood forecasting models.

Box 7.1 illustrates how these measures vary between different types of flood warning system. However, an additional factor to consider is the threshold values which are used for deciding whether to issue warnings since these also affect the performance. In particular – as discussed further in Chap. 8 – there is generally a trade-off to consider between the probability of detection, false alarm ratio and warning lead time. For example, if a river level threshold is decreased, this usually increases the lead time provided and the probability of detecting events but is likely to result in more false alarms. A decision also needs to be taken on how to assess the performance for ‘near misses’, such as when property or infrastructure flooding thresholds were almost reached, or minor flooding occurred within property boundaries but did not affect buildings. For example, residents frequently do not distinguish between a near-miss and a false-alarm, in terms of the inconvenience caused.

In particular, for false alarms, research studies have produced a range of findings ranging from general acceptance of the reasons that they occur through to evidence of the ‘cry wolf’ effect, in which trust in the flood warning service is eroded if they occur too frequently (e.g. Barnes et al. 2007). For example, one view is that they provide an opportunity to check procedures and raise awareness; much like a fire practice drill. However, when they do occur ‘the situation should be explained as quickly as possible to the community through the media, in specially-called public meetings or in discussions with particular groups. An explanation given as soon as possible will help ensure system credibility is retained and will maximise the opportunity to turn a negative into a positive’ (Australian Government 2009a). There is also the possibility of using a probabilistic approach to provide warnings at lower probabilities to specific users, or groups, and this topic is discussed further in Chap. 12.

Box 7.1 Flood Warning Performance for Different Types of System

As discussed in Chap. 1 there are many types of warning service, and it is sometimes useful to consider the following general categories: informal systems which rely on self-help, traditional or indigenous approaches, fully automated systems, and monitoring-and forecasting-systems which rely on inputs from expert staff. Figure 7.3 illustrates some typical values for a selection of performance measures for each type and similar diagrams have also been presented by Nemec (1986), USACE (1996), Environment Agency (2002), and Carsell et al. (2004), amongst others.

The example is for the hypothetical case of a flash flood arising from a short intense burst of rainfall leading to river flooding a short time later. For convenience the rainfall event and onset of flooding are shown at a single point in time, rather than spread over a period of minutes or even hours as would occur in reality. The catchment is also assumed to be saturated and so responds immediately to rainfall. In practice, of course, the actual response time varies between events, depending on antecedent catchment conditions, river flows, rainfall distributions and other factors.

For this scenario, the monitoring and forecasting service has the highest Coverage values, since the use of forecasting models allows a warning service

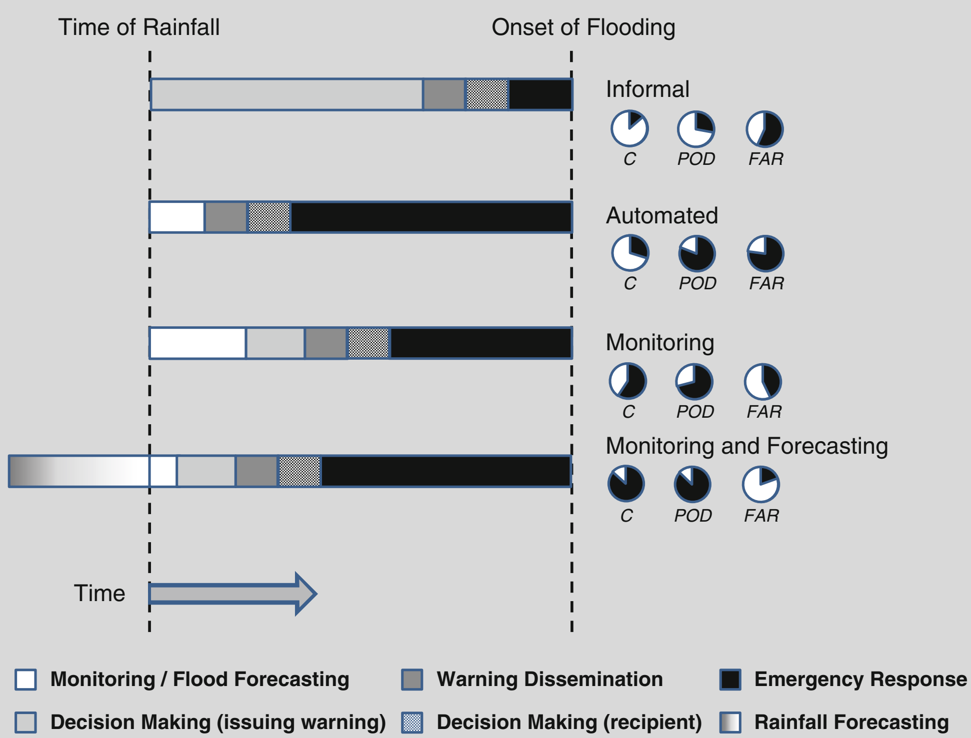

Fig. 7.3 Illustration of the time delays and some key performance measures in the flood warning process for a hypothetical flash flood event for four different types of flood warning service (C = Coverage; POD = Probability of Detection; FAR = False Alarm Ratio; scores are illustrative only and vary widely between systems and locations)

(continued)

Box 7.1 (continued)

to be provided at locations for which a monitoring only approach would not provide sufficient lead time, and possibly for some ungauged locations. The POD values are highest and the FAR values lowest for this case. Of the other types, only the automated approach achieves a similar POD value, but at the expense of a much higher false alarm ratio. Implicit in all of these values is the target warning lead time required by end users, since false alarm ratios usually tend to reduce, and the probability of detection increase, if warnings are issued closer to the onset of flooding. The shaded bars in the figure indicate the times achieved for each approach, which are all considerably less than the catchment response time. The values depend on a number of factors, including the time required to gather data from instruments, run forecasting models and then to disseminate warnings, together with the time taken whilst staff decide whether to issue warnings, and the recipients of warnings decide on the emergency response actions to take.

However, as discussed in Chap. 1, target lead times vary widely and are best determined through experience, consultations and emergency response exercises. Other factors such as the time of day and the severity of flooding can affect the time taken to disseminate warnings or required for an effective response. These examples also illustrate a more general point for flash flood warning systems, which is that one key focus for improvement should be on whether it is possible to reduce any of the time delays in the warning process. For example, as illustrated in Chap. 1, some possibilities include polling instruments more frequently, reducing the run-time for forecasting models, developing decision support tools to assist forecasters, and speeding up the procedures used to issue warnings. In some cases additional time savings are possible by providing local organizations with the authority, training and support to issue warnings locally, rather than waiting for a decision from a regional or national centre.

7.6 Emergency Response Exercises

Having prepared a flood response plan, emergency response exercises – or drills or dry-runs – provide one way to test or validate its components and to identify potential time delays and other problems in the process. The resilience of systems to extreme events can also be tested and interagency coordination evaluated. For some organisations, the requirement to hold exercises forms part of annual performance targets, particularly for locations where flooding only occurs infrequently and for flash flood prone areas. The main types include:

- Tabletop or desktop exercises – office-based exercises in which key participants enact scenarios under the guidance of a facilitator or umpire

- Web-based exercises – scenarios which involve participants situated in a number of different locations, ideally using the same communication systems as they would in an actual flood event
- Full-scale or functional exercises – major exercises which combine elements of both approaches with simulated rescues and flood fighting actions on rivers, lakes and coastlines

To assist in planning an exercise, typically a historical flood event is selected as a basis for the timeline to follow, or a new hydrometeorological scenario is developed. The exercise coordinator then makes the outputs available to participants progressively as the event develops. In some cases, the event is simulated in ‘accelerated’ or ‘compressed’ time to reduce the time required for the exercise.

At the simplest level, approaches such as flipcharts, whiteboards, maps and paper handouts are used to convey and share information between participants. However, larger-scale exercises typically include computer simulations of river and raingauge outputs, weather radar displays and rainfall and flood forecasting model outputs (e.g. World Meteorological Organisation 2011). New factors (or ‘injects’) are then introduced as the event proceeds following a prepared script; for example, event-specific flooding (e.g. debris blockages) or computer, data transmission and communication problems. In some simulations, simulated or pre-recorded radio and television broadcasts are included with role playing to evaluate public relations and media skills.

More generally, computer-based simulations are increasingly used by emergency responders and others for training exercises and rehearsing response plans. This approach has long been established for flight simulation and military applications and recent advances in computer technology have made these techniques more widely available in other applications. The simulation software is typically based on the technologies used in computer games, with one early example being the Incident Commander software developed for the US Department of Justice in the USA for training public response agencies for a range of disasters, including flooding incidents. Some applications have also been developed specifically for flood-related applications, such as a training tool for flood defence (levee) inspectors in the Netherlands on the warning signs of embankment failures (Hounjet et al. 2009).

For multi-hazard exercises, such as those performed by fire and rescue services, the latest approaches make use of purpose-made training centres with a suite of rooms and computer screens, with software able to simulate a wide range of hazards and injects, under variable conditions of temperature, lighting, noise and other factors. The scenery, vehicles, uniforms (for computer-generated ‘actors’) and other features are typically tailored to match the local situation. There is also the potential to enhance simulations by gathering data during real events; for example, by equipping people, vehicles and equipment with GPS-based tracking devices to allow actions to be recorded and replayed in future: a technique which is increasingly used in military simulations. Using web-based software, it is also possible to simulate events across multiple organisations and offices.

However, perhaps the most realistic type of training is a full scale exercise although this is usually more time-consuming and costly to organise. At the simplest level, though, it is often relatively easy to arrange rehearsals of parts of a response plan, such as tests of sirens and other warning dissemination systems, and procedures for transferring the location of a control room or evacuation of a school or government office. Some exercises are considerably more ambitious than this though and take months or years to plan.

For example, Exercise Watermark, which was held on 4 days during March 2011, included exercises at more than 40 locations around England and Wales and involved more than 20,000 people (Defra 2011). This was initiated in response to a recommendation from a post-event review of a major flood event in 2007 which resulted in flooding to more than 50,000 properties in England and Wales (Cabinet Office 2008). The exercise was based on a national-scale flooding scenario which assumed a 4-day period of heavy rainfall falling on already saturated ground and elevated river levels, with a coastal storm surge on the final day. This allowed a range of surface water, river, reservoir failure and coastal flooding issues to be considered, assuming flooding at more than 200,000 properties. Specialist training and exercise management software was used to manage these many different components, including the delivery of simulated news bulletins, flood warnings and social media feeds.

The exercise required collaboration between a large number of government departments, emergency responders, voluntary sector agencies and other organisations. Smaller 'bolt-on' exercises were arranged at 35 locations by local resilience forums, such as evacuation exercises and warning siren tests, as well as numerous community-based activities, such as flood response exercises, water rescues and flood fairs. For the larger-scale components, coordinators could call on helicopters, boats, vehicles and other emergency response assets (e.g. Fig. 7.4), and for local exercises there was the option to interface with the core national exercise.

Another example of a detailed scenario is the ARkSTORM superstorm whose products have been developed for use by "emergency planners, utility operators, policymakers, and others to inform preparedness plans and to enhance resiliency" for use in emergency response planning and exercises in California (Porter et al. 2010). This is one of a series of scenarios which have been developed for California by the U.S. Geological Survey and other agencies for a range of natural disasters, including earthquakes, forest fires, and – in this case – a severe winter storm. The meteorological scenario used (Dettinger et al. 2012) was for the intense rainfall and winds generated by an atmospheric river event, which is a common cause of flash flooding in California (see Box 4.1). Both atmospheric and hydrological models were used to develop realistic conditions for river and coastal flooding and landslides and debris flows. Scenarios were also developed for impacts on infrastructure such as dams and levees, electrical power, roads and highways and water and wastewater treatment works.

7.7 Improvement Plans

Areas for improvement to a flood warning service are often identified from post-event reviews, performance monitoring and emergency response exercises. Improvement plans then need to be put in place to address the issues raised.

Fig. 7.4 Images from Exercise Watermark at sites in Wales and Eastern England during March 2011. *From top left clockwise*: helicopter rescue from a mobile home, mobile command support unit, boat and helicopter rescue from a building, boat rescue from a caravan and car, and a swift-water rescue at a river weir. Note that all rescues were simulated using experienced instructors as 'casualties'

As illustrated in Table 7.5, the types of improvements required typically involve a mixture of technological, organizational, procedural and other changes. In some cases, the investments required are small and easily absorbed within existing budgets; for example, issues with inter-agency coordination commonly arise and can usually be solved by improvements to existing procedures. In many cases, there are also other easily implemented items, or so-called 'quick wins'.

However, where significant investments are required, some prioritisation of options is usually required. As in other areas of flood risk management, the approaches which are typically used include:

- Cost-benefit analyses – comparisons of the cost of the investment with the likely additional damages avoided if the flood warning service is improved
- Independent review findings – the decision to act first on any high priority recommendations identified as part of a post-event review or independent enquiry
- Multi-criteria analyses – analyses which take account of the key priorities identified by stakeholders and possibly other issues such as political pressures for a solution
- Risk-based prioritization – focusing investments on the locations with a high flood risk; in particular where there is a risk to life

The degree to which an investment needs to be justified varies widely between organisations and countries. For example, in some situations priorities are decided by technical managers within the context of an overall or emergency budget allocation. However, in others a detailed business case is required for every investment over a particular threshold value. In most cases, sensitivity studies are advisable to assess the uncertainty in the findings and the robustness of the results.

In some countries, a case can also be made to international funding agencies, and technical assistance requested from regional centres. Also, if an all-hazards approach is used, such as for droughts, wind storms and other hazards, there are sometimes opportunities for sharing costs for items such as monitoring, communications and emergency response equipment. Typically this also results in more frequent use of the system, helping to keep equipment operational and people trained and engaged in the process, which is particularly useful if there are long periods when no flooding occurs. As discussed in Chap. 8, another option with similar advantages is to develop river forecasting models for a range of applications in addition to flood warning, such as for water supply, irrigation, hydropower generation and navigation warnings.

If a prioritisation exercise is required then generally the effort expended needs to be proportionate to the risk and likely costs and tailored to the information available. At an organisational or national scale, perhaps the most widely used technique is cost-benefit analysis (see Box 7.2). For example, this approach has been used in the USA (National Hydrologic Warning Council 2002) and England and Wales (Parker et al. 2005) for flood warning applications.

More generally, for any approach, one challenge is how to include risk to life in the assessment. In some cases, estimates are therefore derived for the likely numbers of fatalities for different flooding situations (e.g. Jonkman et al. 2002; Jonkman and Vrijling 2008; Johnstone and Lence 2009). For example, based on an analysis of selected flood events in Europe, Tapsell et al. (2009) suggest that these "….indicate

Box 7.2 Cost Benefit Analyses for Flood Warning Applications

Cost benefit analyses (CBA or BCA) provide perhaps the most widely used approach to help with justifying investments in a flood warning service. The detail used in the analysis usually depends on a number of factors, including the level of risk, the likely scale of investment, organisational policy and the baseline data available. For example, as discussed in Sect. 7.5, social survey and market research techniques are routinely used in some countries to interview people in locations which have been flooded and to collect information on the damages avoided following receipt of a flood warning. Information on insurance claims and recovery costs from previous flood events can also provide useful insights into the benefits from the provision of flood warnings.

As in other technical areas, the costs are typically estimated by summing the individual components of the investment; for example, considering capital costs together with recurrent costs arising from items such as operations and maintenance, staff salaries, programme management, accommodation (e.g. for an operations centre), communication charges, training, research and development, public awareness campaigns, and equipment repair and replacement. In particular, annual operating costs are often a significant factor and – over a number of years – can significantly exceed the startup costs. In the early stages of establishing a flood warning service, the cost of moving to a 'round-the-clock' (24/7) operation can be a significant additional item on existing budgets. In some cases, emergency response costs are included as well either as a cost or as part of the damage calculations. Payments for the provision of external services, such as weather radar data feeds and meteorological forecasts, sometimes also need to be considered. However, opportunities for cost-sharing can also be explored; for example, as part of a full-flow forecasting system (see main text) or an all-hazards approach.

For flood warning applications, the economic benefits are usually estimated in terms of the damages likely to be avoided – over the long term – due to improvements in the service offered (e.g. World Meteorological Organisation 1973, 2007; USACE 1994; Carsell et al. 2004; Parker et al. 2005). For example, during a flood event, benefits typically accrue from moving vehicles and easily moveable items out of the floodplain and raising larger items such as furniture and electrical goods to higher levels, where possible. These actions sometimes lead to further reductions in the recovery costs, business disruption (direct and consequential) and health impacts following the event. In some cases, additional benefits arise from operational actions to reduce the extent of flooding such as closing flood gates, raising temporary barriers, or installing flood boards at individual properties.

To estimate the long-term benefits, average annual damage approaches are widely used. The damages are typically based on estimates for the frequency and magnitude of flooding at each location under consideration, and

(continued)

Box 7.2 (continued)

assumed relationships between the depth of flooding and the damages caused for different types of building and structures. There are several possible approaches to estimating damages, including the use of historical flood-damage data, unit-area methods, property-value approaches, or weighted average annual damage techniques (see below) (World Meteorological Organisation 2007).

Generally the benefits increase for longer lead times, since this provides more time to move larger items and install additional flood protection measures. However, eventually a point of diminishing returns is reached for lead times much beyond a few hours to days, depending on the application. Separate approaches are sometimes required to assess the potential losses to businesses and industry; for example, by performing site-specific studies for large, high-risk or high-value installations.

However, for flash flood incidents, it is worth noting that the short time available may limit the actions which can be taken to reduce financial losses. More generally, for all types of flooding the actual benefits achieved are also likely to be reduced due to the various social response factors discussed in Sect. 7.5. For example usually only a proportion of those at risk receive warnings, and only a proportion of those people take effective action. These reductions in benefits are typically included in the analysis using multiplicative factors which depend on the warning lead time available and other locally available information. Other factors such as flow velocities, the duration of inundation, contamination, debris/sediments, rate of rise, frequency of flooding and the time of day and season are sometimes considered (e.g. Merz et al. 2010).

For example, Molinari and Handmer (2011) propose an event-tree based approach for assessing the effectiveness of flood warnings which includes many of these factors under the general headings of warning, noticing, understanding, considering a target (i.e. that the warning applies to them), trusting, confirming and acting. Parker et al. (2008) also propose a model which takes account of a number of actions which can be performed in the lead up to and during a flood event. These include the benefits of flood defence operations, community-based options (e.g. temporary defences, pumping), watercourse maintenance (e.g. removing blockages, clearing debris screens), search and rescue, evacuation, contents moved or evacuated, contingent flood proofing (e.g. flood boards installed following a flood warning) and deployment of business continuity plans.

When using depth-damage relationships, ideally these should be based on local surveys and interviews, and this can require a considerable amount of investigation if there is no information available from previous studies. For example, USACE (1994) cites the following questions which a plant manager

(continued)

Box 7.2 (continued)

might ask during a flood damage survey: "How much warning time do I have?" "Does the flood occur at night or during the day?" "Will riggers and trucks be available to move my equipment?" "Will there be ice in the water?" "What kind of sediment load will be carried?" "Should I assume oily water like last time or clear like the time before?" "My inventory and goods in process vary from day-to-day, week-to-week, and month-to-month with seasonality of my business, what should I assume?" "Do you want conditions for the recession we're in now or for one of our best years?" "What is the duration of the flood?".

Following these types of analysis, the benefit-cost ratio is then typically estimated taking account of forecasts for inflation, rises in living standards, depreciation and other anticipated changes in the financial environment over the planning horizon. Allowances also need to be made for any previous studies which have already allocated a proportion of the estimated benefits. A decision then needs to be taken on what constitutes an acceptable ratio when comparing benefits and costs and this varies widely between organisations. Alternatively, the relative values for different options are sometimes used as a basis for prioritization. Sensitivity tests or Monte Carlo analyses can also help with understanding the robustness of the results, and the likely uncertainty in the findings. As noted earlier, there are potentially additional benefits to consider from using a probabilistic approach to issuing flood warnings and this topic is discussed in more detail in Chap. 12.

four broad sets of flood characteristics that can be identified which are seen to influence the number of fatalities or injuries:

- Area characteristics (exposure, density of population, type and structure of buildings affecting building collapse)
- Flood characteristics (depth, velocity, debris, speed of onset, time of day/year)
- Population characteristics (age, prior health, disability, language constraints, presence of tourists/visitors, behavior – including driving through floodwaters, risk awareness)
- Institutional response (flood warnings, evacuation, rescue)"

For example risk-to-life approaches are widely used in dam break studies (see Chap. 11) and the resulting estimates are often a key driver for prioritizing inspection and maintenance programmes and in emergency response planning (e.g. Needham 2010).

Another consideration is that, in less-developed economies, and particularly for subsistence farmers, the impacts of flooding are often small in financial terms but have a large effect on incomes and health. In that case, ideas from the disaster risk reduction literature (e.g. Yodmani 2001; ECLAC 2003; Brown 2008) are potentially useful; for example considering the effects on activities such as fishing, livestock rearing and farming in terms of both livelihoods and income. More generally, there are typically a range of other benefits from a flood warning service which cannot easily be quantified in monetary terms, and these are often called intangible losses or benefits. For example, some items which might be considered for both tangible and intangible benefits (USACE 1996) include:

- Reduced threat to life – barricades, evacuations, rescues, public awareness
- Reduced property loss – removal or elevation of residential and commercial structure contents and vehicles
- Reduced social disruption – traffic management, emergency services, public awareness
- Reduced health hazards – evacuations, public information, emergency services
- Reduced disruption of public services – utility shutoffs, emergency services, supplies, inspection supplies, inspection, public information
- Reduction in inundation – flood fighting, temporary flood damage reduction measures, technical assistance

However, despite the various challenges involved, cost-benefit techniques are widely used and are a useful tool for understanding both relative priorities for investment, and the items to focus on first. This approach can also be included as part of a wider multi-criteria analysis, using scoring, weighting or other techniques to assess the relative importance of a range of social, environmental and economic factors. For example, a multi-criteria approach might be used for an initial ranking of options before a more detailed cost-benefit analysis of short-listed options, or to rule out unacceptable options at the outset (e.g. World Meteorological Organisation 2007; Department for Communities and Local Government 2009). As discussed earlier, maps of socioeconomic, environmental and other vulnerability factors are also useful to identify local 'hot-spots' and other priority areas.

For example, one multi-criteria approach to prioritizing requests for new flood warning schemes (SNIFFER 2009) considered the following tangible and intangible benefits:

- Minimising the risk of death or serious injury
- Reducing the social impacts of flooding (including impacts on vulnerable groups)
- Enabling householders to remove or protect property
- Enabling business and agriculture to remove or protect property
- Enabling Local Authority operation of flood defence assets or carrying out other operations
- Reducing disruption to infrastructure

In some countries, map-based (GIS) decision-support tools are sometimes used for an initial assessment. For example, in the USA, the HAZUS-MH software is widely used to estimate direct damages to general building stock, essential facilities, transportation systems and utility systems, and other costs and losses such as the cost of repair, income loss, crop damage, casualties, and shelter needs (FEMA 2011). Some other countries have similar systems or procedures.

Risk-based techniques are also widely used to target investment in monitoring, forecasting and warning improvements (USACE 1996; Andryszewski et al. 2005; Tilford et al. 2007). More generally, there is increasing interest in using probabilistic techniques to help to maximize the benefits of a flood warning service and Chap. 12 discusses some approaches to assessing the incremental benefits in moving from a deterministic to a probabilistic system.

7.8 Summary

- The effectiveness of a flood warning system is strongly dependent on the quality of the preparations made between flood events. Typically these include flood risk assessments, flood response planning, post-event reviews, performance monitoring, emergency response exercises, and the development and implementation of improvement plans. In the emergency planning literature, the term 'preparedness' is normally used to describe these types of activities
- Techniques for assessing flash flood risk include reviews of historical evidence, flood modelling and consultations with residents in flood prone areas. In recent years the use of hydrodynamic modelling techniques has become widespread for rivers and urban areas when suitable calibration information is available. Often these studies are supported by high resolution digital elevation mapping. However, due to data and other limitations, simpler empirical techniques are still widely used for some types of flash floods, such as debris flows. Once the risk has been assessed, the findings then need to be translated into operationally useful outputs such as flood warning and evacuation maps and databases of property addresses and contact details
- Flood response plans describe the actions to be taken during a flood event. Typically these need to be prepared by (or for) all key participants in the warning and response process, including communities, emergency responders, civil protection authorities and hydrological and meteorological agencies. Some particular areas for attention include the assistance to be provided to vulnerable groups, the risks to critical infrastructure, and evacuation planning.
- Many flood warning services routinely produce post-event reviews following major flood events and contribute to wider multi-agency reviews. Typically post-event reports describe the causes and impacts of flooding, the performance of flood warning and forecasting systems, asset performance, the damages avoided, interagency collaboration, and the lessons learned. This information is then used to guide recommendations for future improvements
- Performance monitoring provides a useful tool for assessing how a flood warning service develops over time and performs in specific flood events. This then helps to identify areas for improvement in monitoring, forecasting and warning systems and operational procedures. The performance measures used normally consider the social response to flood warnings as well as the purely technical

aspects of monitoring and forecasting systems. These are sometimes incorporated into organizational targets and service level agreements

- Emergency response exercises are widely used to test flood response plans and to identify areas for improvement. They also help to promote interagency collaboration and maintain staff skills between flood events. The types of exercises used range from simple tabletop exercises through to full-scale exercises involving multiple organisations at multiple locations. Computer simulation technologies are increasingly used to add to the realism of scenarios
- Post-event reviews, performance monitoring and emergency response exercises often highlight areas for future improvements. Sometimes these are mainly organisational or procedural and have few cost implications. However, when significant investments are required, some approaches to the prioritisation of improvements include cost-benefit, multi-criteria and risk-based analyses. However, the methods used need to be tailored to the information available and to the socioeconomic circumstances of the communities at risk

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Chapter 8
Rivers

Abstract Flash floods in rivers usually arise from heavy rainfall, although snowmelt is sometimes a factor. The extent and magnitude of flooding may also be influenced by event-specific factors such as blockages by debris and ice jams. This chapter discusses approaches to estimating the flood risk in these situations and the main monitoring, warning and forecasting techniques which are used. These include Flash Flood Guidance methods and site-specific approaches using river level thresholds and flood forecasting models. Forecasting and warning techniques for reservoirs and flow control structures are also discussed.

Keywords Flood risk assessment • Thresholds • Flash flood guidance • Site-specific warnings • Ice jams • Reservoir operations • Flow control structures

8.1 Introduction

Flash floods on rivers, streams and other watercourses are a common occurrence in many countries. In arid regions floods sometimes appear in dry river beds; however, more usually, levels rise quickly from low to moderate flows. This then presents a risk to people and property when water goes out of bank or overtops flood defences or levees. In some cases, there is also a risk at lower levels, such as to hikers in canyons and vehicle drivers at low-water crossings.

The definitions of flash floods vary between countries and – as discussed in Chap. 1 – some typical criteria which are used include the catchment response time or typical catchment and storm scales. However, improvements in monitoring, forecasting, and warning techniques are increasingly allowing a flood warning service to be offered for faster-responding catchments than was possible in the past. For some organizations, this has meant that what was previously regarded as a technical challenge is now seen as routine in terms of issuing operationally useful warnings.

K. Sene, *Flash Floods: Forecasting and Warning*, DOI 10.1007/978-94-007-5164-4_8,

Table 8.1 Some examples of river flash flood events

Cause	Location	Year	Impacts	Cause
Rainfall	Big Thompson Canyon, Colorado, USA	1976	144 fatalities and damage to 418 homes and businesses, many mobile homes, cars, bridges, roads and structures. 250 people were reported as injured and more than 800 were evacuated by helicopter the following morning	A complex system of thunderstorms remained for more than 3 h over the Big Thompson Canyon area, producing as much as 300–350 mm of rainfall and 190 mm in one hour. The storm was limited to a narrow band 8–16 km wide (USGS 2006)
Rainfall	Gard Region, southern France	2002	A widespread flood event resulted in 23 deaths and economic damages valued at about 1.5 billion dollars (Anquetin et al. 2009)	An extensive slow-moving mesoscale convective system resulted in a peak 24 hour rainfall total of 600–700 mm (with 200 mm exceeded over an area of 5500 km^2) and 6 hour totals of 200–300 mm (Delrieu et al. 2005)
Rainfall	Boscastle, southwest England	2004	Approximately 1,000 people were affected by the event, with about 100 people rescued by helicopter and 116 cars swept out to sea (North Cornwall District Council 2004)	A mid-summer thunderstorm resulted in a peak hourly rainfall of more than 80 mm at one raingauge, with a 24 h total in the area of about 200 mm
Ice jam	Montpelier, Vermont	1992	Hundreds of residents were evacuated, 120 businesses were disrupted, and many cars damaged (Abair et al. 1992)	A large ice jam broke loose at one bridge in the city only to form a dam at another bridge, leading to flooding of much of the downtown area within an hour

Table 8.1 provides several examples of the types of flash flood which can occur in rivers. The main cause is usually heavy rainfall but in some cases flooding is exacerbated by factors such as snowmelt and debris or ice jams at bridges and other locations. Operations at reservoirs and flow control structures sometimes also present a risk.

This chapter introduces the main approaches which are used for assessing flood risk and deciding whether to issue flash flood warnings for rivers. Techniques for ice jams and reservoir and control structure operations are also discussed. Further background is provided in Chaps. 2–6 which consider the main monitoring, forecasting and warning techniques used for flash floods. Chapter 7 also discusses some of the longer-term planning (or ‘preparedness’) tasks which are usually required to ensure the success of a warning system, such as developing flood response plans, emergency response exercises, community-engagement activities, post-event reviews and performance monitoring.

For further background, there are several comprehensive guidelines on establishing flood warning systems for rivers; in some cases with an emphasis on flash floods. These include examples from the USA (USACE 1996; NOAA/NWS 2010; FEMA 2006), Australia (Australian Government 2009a) and internationally (APFM 2007; NOAA 2010; World Meteorological Organisation 2011). Box 8.1 also describes a flash flood warning service in southern France which illustrates many of these principles, and Chap. 1 provide examples of regional and community-based approaches for river flash floods.

Box 8.1 Flash Flood Warning System, Southern France

Flash floods present a considerable risk in the south of France. Some notable examples in recent years include the catastrophic events of June 2002 in the Gard region (Delrieu et al. 2005) and June 2010 in the Draguignan area (Javelle et al. 2012). Flash floods typically arise in the summer and autumn months from slow-moving convective storms which draw moisture from the Mediterranean, with the rainfall enhanced by topographic influences.

Although a national flood forecasting and warning service is provided for major rivers, on many smaller rivers there is no river monitoring equipment, and events can develop rapidly, providing little time for issuing warnings. To address this problem, an early warning system for the Mediterranean regions of southeast France was introduced in 2004 called "Adaptation d'Information Géographique pour l'Alerte en Crue" or AIGA. The service is operated by Météo-France and was developed by Cemagref in collaboration with Météo-France (http://www.irstea.fr/).

The modelling approach which is used was developed for smaller catchments typically with areas from a few tens to a few hundreds of km^2. The main rainfall inputs consist of 15-min weather radar observations from the Météo-France network of C-band and S-band radars. These are adjusted using raingauge observations for which the typical coverage in this area is about 1 gauge per 100 km^2.

The basis of the method is to compare runoff estimates derived using a simple distributed rainfall-runoff model with long-term climatological values (Javelle et al. 2010). In this approach, the runoff production for each grid square is estimated using a simple conceptual model, which is initialised using a daily soil moisture accounting model. The total catchment discharge is then estimated by combining these values using an appropriate routing time delay, with a focus on estimating peak flows rather than the full flow hydrograph. The model is operated at a grid scale of 1 km.

(continued)

Box 8.1 (continued)

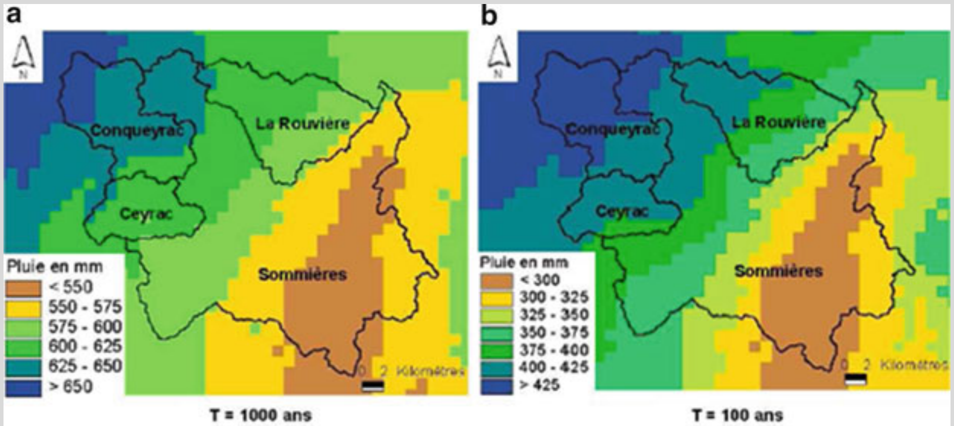


Fig. 8.1 Example of climatological maps of 24-h rainfall totals for 1 in 1,000 year and 1 in 100 year return periods derived using a rainfall generator approach (Lavabre and Gregoris 2006)

Flash flood warnings are issued on the basis of comparisons of the runoff estimates with threshold values based on the following return periods:

- Yellow for events with a return period of 2–10 years
- Orange for large events, defined as having a return period of 10–50 years
- Red for rare events, defined as having a return period of more than 50 years

Threshold values are estimated using long-term hindcasts in which the regional rainfall inputs to the model are derived using a rainfall generator (Arnaud and Lavabre 2002; e.g. Fig. 8.1). In operational use, colour-coded maps are generated every 15 min and published to a website for use by local authorities. The underlying outputs are also available to perform more detailed analyses, if required. Rainfall accumulation maps are also provided with alerts provided based on rainfall depth-duration thresholds.

The method has been shown to provide useful additional lead time to the emergency services for a number of severe flash flood events in southern France, and to provide a useful back-up on larger rivers in case of failure of telemetered river gauges during a flood event.

For example, during the Draguignan event of 2010, the system provided an hour or more of advance warning to the emergency services. The event arose from a widespread area of slow-moving thunderstorms, with rainfall intensities approaching 80 mm h^{-1} in some locations and an event total rainfall of 461 mm recorded at one raingauge. In Draguignan itself, the onset of flooding was at about 4 pm with a large increase in levels at 5 pm. The AIGA output for 4.15 pm (Fig. 8.2) indicated that the discharge had just exceeded the 50-year flood level in the Nartuby river which passes through the town (Javelle et al. 2012). Flooding in the central street of Trans-en-Provence, 5 km further

(continued)

Box 8.1 (continued)

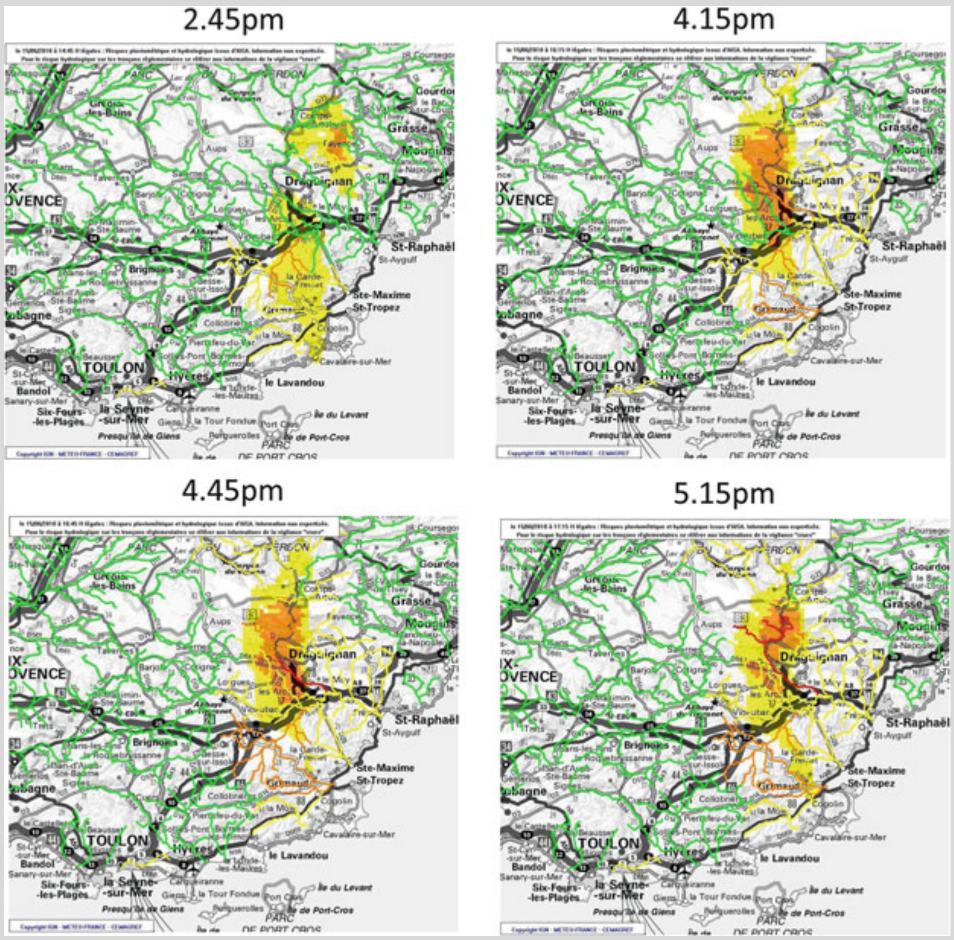


Fig. 8.2 Situation according to the AIGA method between 2.45 and 5.15 pm (local time) on 15 June in the Draguignan area: *yellow, orange and red coloured rivers* correspond to estimated discharges exceeding the 2, 10 and 50-year flood (Javelle et al. 2012)

downstream, started at about 5.30 pm and during the evening at other locations further downstream. The catchment response time to Draguignan is typically about 6 h.

During the event approximately 2,450 people were rescued. According to the emergency services "….the situation reported by AIGA was one of the elements taken into account to decide to put the alert at its maximum level and to ask for more intervention resources. It helped the emergency services to have a 'synthesized' view of the situation, while they in the meantime had to deal with a multitude of partial and local information emerging from the field, sometimes with difficulty due to communication problems (for example caused by the mobile network crashing down)" (Javelle et al. 2012).

(continued)

Box 8.1 (continued)

The outputs from this approach are routinely evaluated in terms of performance statistics such as the Probability of Detection and False Alarm Ratios, and forecast lead-time. Generally the results show that the method improves on the use of rainfall threshold values alone since these take no account of catchment antecedent conditions. To assist in the evaluation process, where possible the information collected following flood events includes the event total rainfall, peak river level and flow observations, damage reports from local authorities, and survey data of high water levels.

Some current areas of research include the use of rainfall forecasts in the runoff estimation procedure, new approaches to catchment modelling, refinement of threshold values, and use of dual polarisation radar outputs. Shorter range gap-filling X-band weather radars are also being evaluated for flash flood prone areas in the southeast of France (Kabeche et al. 2010). More generally, work is underway to build closer integration of AIGA outputs into community flood response plans.

8.2 Flood Risk Assessments

To assess the risk from river flooding, many countries have flood risk mapping programmes in place, including the USA, Canada, Japan, and a number of European countries. The results are often made openly available in publications and via websites.

The formats used differ widely but typically include the anticipated extent of flooding for different return periods, such as the 1 in 10, 20, 50 and 100 year values, although increasingly results are expressed in terms of annual exceedance probabilities. Estimates for depths, velocities, durations, historical flood extents and other items are sometimes also included, such as comparisons of the flood extent with flood defences (levees) both fully functioning and completely failed (e.g. ICHARM/MLIT 2005; EXCIMAP 2007; Meyer et al. 2011).

Chapter 7 describes some of the sources of information which are typically used to help to assess flood risk, including historical evidence, post-event surveys, and remote sensing data. However, for river flooding applications, modelling techniques are also widely used and some typical approaches include:

- Statistical analyses to derive inflows for use with a steady state hydraulic model or a simpler normal depth approach; inflows are typically estimated from a flood frequency analysis or empirical relationships relating peak flows to catchment characteristics and other factors
- Rainfall-runoff modelling based on design storms derived using a rainfall frequency analysis and typical storm profiles, with the resulting inflows used as input to one- and two-dimensional hydrodynamic models of varying complexities

Flood frequency estimates are typically derived by fitting a probability distribution to historical annual maximum flow values. These are typically based either on observations for a single site or on pooled values for a number of similar sites to help to overcome issues with short record lengths and/or ungauged locations. The types of distributions used vary between organisations but some widely used examples include the Generalised Extreme Value and log-Pearson distributions (e.g. World Meteorological Organisation 1989).

The complexity of the approach is typically tailored to the anticipated level of flood risk, the length of river under consideration, and available budgets; for example, for a major city use of a two-dimensional hydrodynamic model may be justified whilst, for a region-wide analysis in a rural area a simpler approach is often more appropriate. If a rainfall-runoff model is used then typically a unit hydrograph approach is adopted, with the resulting peak inflows sometimes scaled based on a comparison with the values estimated from a flood frequency approach. The hydrodynamic component is usually constructed on the basis of river channel survey data and a digital elevation model for the floodplain. Floodplain elevations are normally obtained from ground-based survey, satellite altimetry using Synthetic Aperture Radar (SAR) and/or Light Detection and Ranging (LiDAR) survey taken from an aircraft or helicopter. For example, vertical accuracies of 0.05–0.25 m are now possible with airborne LiDAR at a spatial density of at least one point every 0.25–5 m (e.g. Mason et al. 2011).

The resulting models are sometimes complex with large numbers of catchment inflow points and hundreds or thousands of nodes in the hydrodynamic component. Within and around flood-prone areas, the key structures which influence levels and flows are usually also surveyed, such as bridges, weirs and flood embankments. Monte Carlo techniques are also useful in some applications, such as when considering the potential impacts of flood defence (levee) failures (e.g. Gouldby et al. 2008). Compared to more qualitative techniques, one advantage of a modelling approach is that estimates for the probability of flooding can be combined with information on the potential consequences to provide an overall assessment of flood risk. Some typical applications of the resulting estimates then include:

- Providing a guide to areas in which future residential and other development should be discouraged or prohibited
- Estimating potential flood damages to assist in the prioritization of investment in flood risk mitigation measures, both structural and non-structural
- Identifying critical infrastructure at risk to assist with contingency planning and to prioritise risk reduction measures
- Identifying vulnerable groups requiring particular assistance during flood events (see Chap. 7)

Often sensitivity studies are performed to assess the uncertainty in the resulting estimates to the assumed inflows and model parameters, and probabilistic techniques can be used to provide a more formal assessment of the uncertainty (e.g. Pappenberger et al. 2007; Beven et al. 2011).

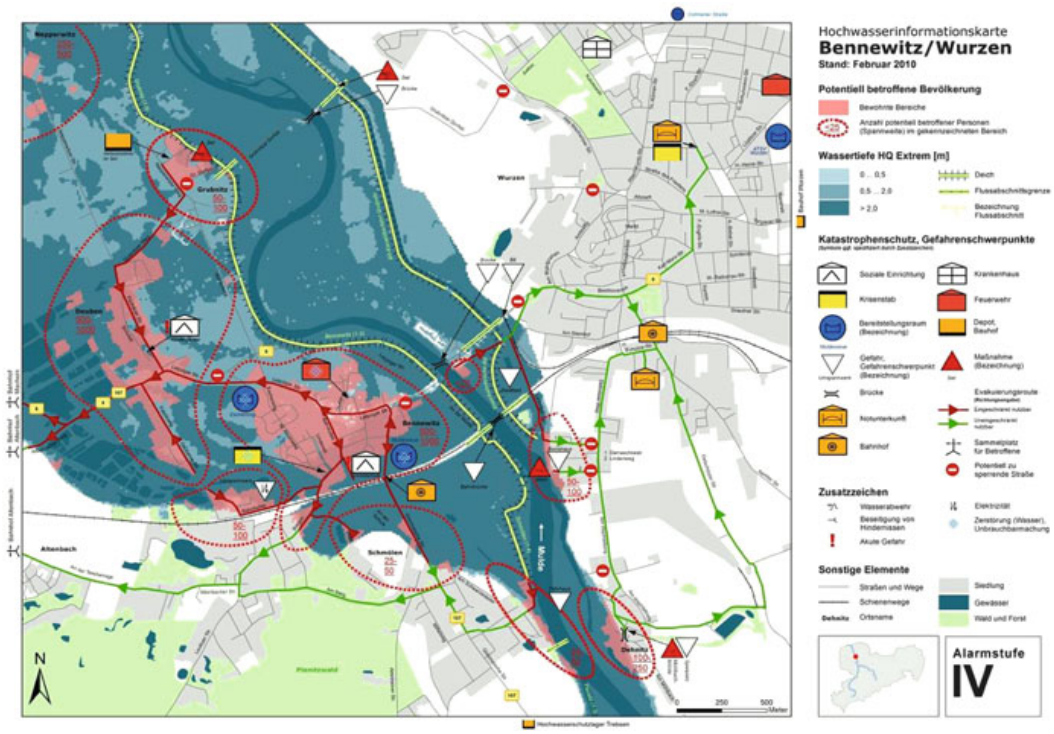


Fig. 8.3 Example of a map for emergency management developed as part of a European research study into good practice in flood risk mapping for different applications. This example was developed as part of a case study for the municipality and city of Bennewitz/Wurzen in Germany and shows the coordination centre, assembly points, evacuation routes, critical infrastructure, inundation depths and estimates for the affected population (Meyer et al. 2011)

As discussed in Chap. 7, flood warning and evacuation maps can also be produced to summarise operationally useful information, such as the example shown in Fig. 8.3. Tabulated products are also widely used, such as lists or databases of properties at risk from flooding for different river gauge heights. These can then be used as a starting point for generating subscriber lists for automated phone dialing or multi-media warning dissemination systems, and by emergency response staff during flood events (see Chap. 6).

For a national flood risk mapping programme, the priority is often to start with the highest risk locations, such as major towns and cities, which are typically situated alongside large, lowland rivers. Smaller flash flood prone tributaries are then included at a later date; however, one challenge is often a lack of data for model calibration and uncertainties about the influence of debris and other event-specific factors. Also, when many small catchments are potentially at risk, but with no recent flooding history, it may be difficult to justify a detailed modelling study at every location.

These considerations have led to the development of more empirical approaches for assessing the risk from flash floods (e.g. NOAA 2010). Typically a range of risk factors or indices (e.g. on a scale of 0-1) is identified based on an analysis of previous events in a region. Table 8.2 shows some potential candidates. Areas at risk

Table 8.2 Some examples of potential indicators for use in flash flood risk assessments, in addition to the catchment area

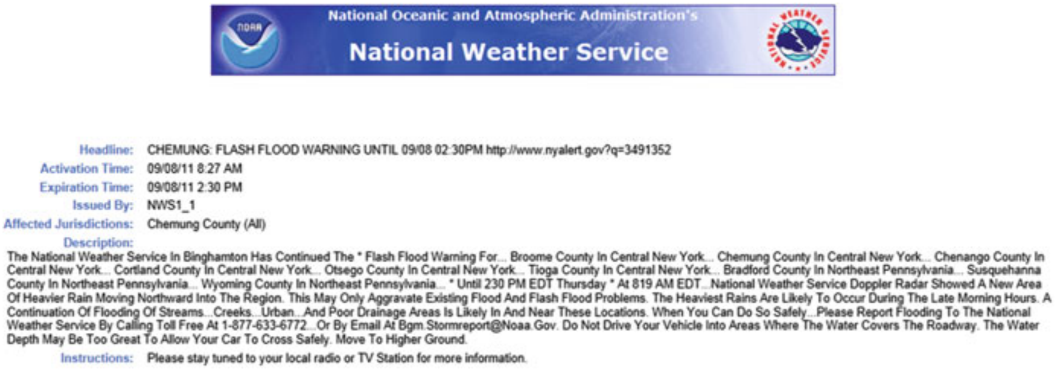
Category	Description
Arid zones	Estimates or indices for the likely infiltration rates in river channels following dry periods, and indicators linked to soil infiltration capacity; for example for soils that are compacted or dried to a crust and have little capacity to absorb heavy rainfall
Catchment response times	Estimates for the typical time delay between the heaviest rainfall and peak flows based on historical data and/or unit hydrograph techniques
Channel characteristics	Factors expressing the influences of sedimentation on channel carrying capacity, which is a serious issue in many countries due to catchment degradation, and of other factors such as seasonal vegetation growth
Land use	Spatial coverages of land use types including farmland, forests, grasslands, and urban areas
Slope	A key factor affecting velocities and catchment response times, and the erosive potential of flows
Soil types	Spatial coverages of indices for soil types such as clays, sands, loam and other categories, which all have different runoff responses to rainfall
Snowmelt	Factors expressing the risks of sudden increases in river depths and flows from snowmelt following a sudden rise in air temperature and/or heavy rainfall falling on snowpack
Structures	Factors indicating the potential for bridges, culverts, weirs and other features of the built environment to impede the passage of high flows and/or trap debris

from flash flooding are then mapped based on a weighted combination of factors or regression relationships between peak flows and key indices. For example, in the USA, Flash Flood Potential Index maps are used in some forecast offices as a backdrop to flash flood guidance outputs and are based on a combination of the following criteria: slope, soil type, forest cover, and land use. Some potential real-time applications of these types of approach are discussed briefly in the following section.

8.3 Warning Systems

8.3.1 Flood Alerts/Watches/Early Warnings

There are many challenges in issuing warnings for river flash floods. In addition to uncertainties about the likely location, timing and magnitude of flooding, event-specific factors such as debris blockages may increase the risk. The rapid onset of some events also leaves little time for decision-making, and floods sometimes occur


National Oceanic and Atmospheric Administration's
National Weather Service

Headline: CHEMUNG: FLASH FLOOD WARNING UNTIL 09/08 02:30PM http://www.nyalert.gov?q=3491352
Activation Time: 09/08/11 8:27 AM
Expiration Time: 09/08/11 2:30 PM
Issued By: NWS1_1
Affected Jurisdictions: Chemung County (All)
Description:
The National Weather Service In Binghamton Has Continued The * Flash Flood Warning For... Broome County In Central New York... Chemung County In Central New York... Chenango County In Central New York... Cortland County In Central New York... Otsego County In Central New York... Tioga County In Central New York... Bradford County In Northeast Pennsylvania... Susquehanna County In Northeast Pennsylvania... Wyoming County In Northeast Pennsylvania... * Until 230 PM EDT Thursday * At 819 AM EDT...National Weather Service Doppler Radar Showed A New Area Of Heavier Rain Moving Northward Into The Region. This May Only Aggravate Existing Flood And Flash Flood Problems. The Heaviest Rains Are Likely To Occur During The Late Morning Hours. A Continuation Of Flooding Of Streams...Creeks...Urban...And Poor Drainage Areas Is Likely In And Near These Locations. When You Can Do So Safely...Please Report Flooding To The National Weather Service By Calling Toll Free At 1-877-633-6772...Or By Email At Bgm.Stormreport@Noaa.Gov. Do Not Drive Your Vehicle Into Areas Where The Water Covers The Roadway. The Water Depth May Be Too Great To Allow Your Car To Cross Safely. Move To Higher Ground.
Instructions: Please stay tuned to your local radio or TV Station for more information.

Fig. 8.4 Example of a flash flood warning issued for Chemung County by the NOAA/National Weather Service in September 2011 during Tropical Storm Lee; see Box 6.1 for further details (http://www.nyalert.gov/home.aspx)

in catchments with no river gauge telemetry. This often leaves flood warning staff with little or no on-the-ground information until reports are received of flooding incidents from the public and emergency response organisations.

For locations with a high flood risk or a history of flash flooding, it is often possible to justify installing river level instrumentation to provide site-specific warnings (see Sect. 8.3.2). However, in many situations, even a more general alert is useful. For example, Hall (1981) notes that for '…flash flood forecasting, the main requirement may be the quick identification of the fact that critical danger thresholds will be surpassed rather than the accurate definition of the magnitude and timing of the flood peak'. Chapters 6 and 7 also discuss the role of 'self-help' or informal approaches for raising alerts, such as when upstream communities warn those downstream by phone or radio, based on indicators of potential flooding such as heavy rainfall, rapidly rising river levels and changes in water colour or turbidity. In some cases this type of descriptive information is incorporated into more formal systems; for example by sharing reports from volunteers and other observers using a web-based decision support system (see Chap. 6).

More generally, many meteorological and hydrological services provide some form of general alert, watch or early warning service for the risk of flash flooding. The resulting information is typically provided to civil protection authorities, emergency responders and representatives of community-based warning systems, and in some cases directly to the public. The level of detail provided is typically at catchment, county, district or regional scale (e.g. Fig. 8.4) and contrasts with site-specific warnings which – in the best cases – provide an indication of the likely start time, depths, duration and extent of flooding at specific groups of properties in towns, villages and other locations.

For flash flood alerts, some examples of the types of information conveyed include advice that vehicle drivers should be particularly careful at river crossing points and not drive through flood water, and that people should take extra care when walking, cycling, camping, hiking, or working near rivers, streams, creeks, canyons etc. Key organisations can also be informed of the potential for flooding and some low-cost, low-impact activities started for which a false alarm only has minor consequences, such as the following examples:

- Access – local authorities or businesses placing (or activating) advisory signs for high risk locations such as canyons and riverside car parks, paths and campsites
- Flood response plans – organisations and communities activating plans and moving to an increased state of alert; for example starting more frequent monitoring and forecasting, holding phone conferences to discuss the developing situation, informing critical infrastructure operators, and checking that communications and emergency response equipment is available and operational
- Flood response – local authorities and others taking precautionary measures, such as clearing debris from watercourses with a known flood risk and pre-positioning staff and equipment closer to areas potentially at risk

Perhaps the simplest approach to providing a general alert is to use rainfall depth-duration thresholds (e.g. 30 mm in 2 h, 50 mm in 4 h). Tables or maps of typical times of travel for floods in the river network often provide a useful complement. The rainfall inputs are typically obtained from raingauges or weather radar observations, although multi-sensor precipitation products and rainfall forecasts are increasingly used where available (see Chaps. 2 and 4). Rainfall depths are usually evaluated against threshold values either manually or within a telemetry or flood forecasting system (see Chaps. 3 and 5).

Threshold values are typically defined based on historical rainfall records and information from previous flood events on the locations and impacts of flooding. Once in operation, regular performance reviews are then required; for example using categorical statistics such as the Probability of Detection and False Alarm Ratio (see Chaps. 4, 5 and 6). However, the risk of false alarms and missed warnings is intrinsically higher than for other approaches since no account is taken of current catchment conditions. Rainfall forecasts also introduce additional uncertainty into the process, particularly at longer lead times. As discussed in Chaps. 4 and 10, meteorological services therefore increasingly issue heavy rainfall warnings on the basis of probabilistic threshold criteria (e.g. Koistinen et al. 2012; Met Office/Environment Agency 2010).

In practice, rainfall depth-duration thresholds are therefore often only used for an initial ‘heads-up’ regarding the risk of flash flooding. However, rainfall thresholds alone can be useful in situations where catchment conditions are less of a factor, such as in some arid regions, and are widely used for debris flows (see Chap. 9) and in urban areas (see Chap. 10).

Where catchment conditions are important, these are usually represented using indicators such as the Soil Moisture Deficit or cumulative rainfall in recent days, or indices such as the Catchment Wetness Index, Base Flow Index, or Antecedent Precipitation Index (e.g. USACE 1996; World Meteorological Organisation 2009). As discussed in Chap. 3, due to the wide spatial variability in values, soil moisture values are normally estimated from a model rather than from direct observations. Warning threshold values then need to be calibrated using the same types of observations that will be used in real-time, such as raingauge or weather radar data. In some cases a catchment model is used to help in this process, assuming various combinations of soil moisture deficits and rainfall depth-duration values and storm profiles to identify the conditions most likely to lead to flooding. If flooding thresholds are unknown, then flood frequency estimates are often used. For example, geomorphological studies typically suggest that bank full flows in rivers correspond to peak flows with return periods of about 1–5 years (e.g. Leopold et al. 1995; Schneider et al. 2011) and values of this order are widely assumed in flash flood modelling studies.

Perhaps the earliest and most widely used example of this approach is the Flash Flood Guidance (FFG) method which was developed in the USA in the 1970s (e.g. NOAA/NWS 2003; Georgakakos 2006). This was designed for use with the national weather radar network and threshold values were initially defined at a catchment scale. The approach is typically used to provide a warning service for ungauged catchments where there are no telemetered river level observations to help in providing

Box 8.2 Flash Flood Guidance, USA

Flash flood guidance can be defined as "…the average rain needed over an area during a specified period of time to initiate flooding on small streams in an area" (Sweeney 1992). The main components in the approach include:

- Rainfall Inputs – radar rainfall or multi-sensor precipitation estimates, and rainfall forecasts
- Soil moisture estimation procedures – the use of operational rainfall-runoff models for estimating catchment state both off-line and in real-time
- Threshold runoff – estimates for the runoff that would cause a small stream at the catchment outlet to slightly exceed bankfull levels
- Decision-support tools – map-based pre- and post-processing tools to assist forecasters in decision-making

The details of the implementation differ between River Forecast Centres depending on local catchment characteristics, the models used and data sources. Until recently, catchment conditions were usually estimated using the lumped Sacramento Soil Moisture Accounting (SAC-SMA) conceptual rainfall-runoff model (Burnash 1995). However, distributed modelling approaches are increasingly used to generate Gridded FFG outputs (GFFG; Schmidt et al. 2007), leveraging soil moisture output from the NOAA/National Weather Service distributed modelling framework (Koren et al. 2004) which is discussed in Box 5.1.

Operationally, for each location and rainfall duration, the key information required is the threshold runoff and a set of rainfall-runoff curves valid for current catchment conditions. These curves are derived using soil moisture outputs from the operational hydrological model and are regularly updated as catchment conditions change; for example at 6-hourly intervals. Threshold runoff values are typically derived as a one-off exercise using unit hydrograph techniques and assumptions about the flows that correspond to bankfull levels (e.g. flows with a 1 in 2 year return period).

(continued)

Box 8.2 (continued)

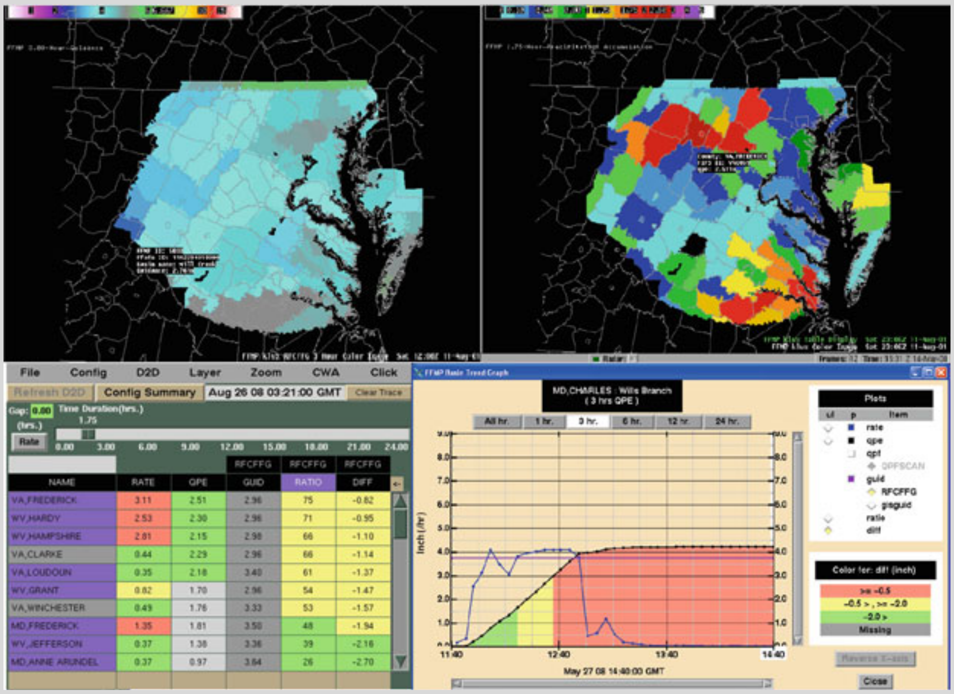


Fig. 8.5 Examples of some of the outputs available in the NOAA/National Weather Service Flash Flood Monitoring and Prediction system (for various locations, durations and time periods): Flash Flood Guidance map, Precipitation Accumulation map, Basin Trend graph, Basin Table output (NOAA/NWS 2008)

The Flash Flood Guidance is then estimated as the depth of rainfall for each assumed duration which – under current catchment conditions – would generate the threshold runoff. This can be compared with observed or forecast average basin rainfall values. Typically these calculations are performed using a decision-support tool called the Flash Flood Monitoring and Prediction Program (FFMP; Fig. 8.5), together with related tools for generating FFG values and making local adjustments.

For example, the FFMP system presents maps of a region and individual catchment. Other useful background information can be added, such as known or estimated flash flood risk locations; for example expressed in terms of a Flash Flood Potential Index. A 'Flash Flood Index' is also calculated depending on the amount by which rainfall values exceed the guidance values. Some continuing areas for FFG research include developing improved techniques for forecast verification, applying the method to urban areas (e.g. NOAA/NWS 2003), and refining the method for parts of the USA where land forms and rainfall intensity influence the occurrence of flash flooding more than soil moisture (e.g. some desert areas). Related work also seeks to widen the use of distributed models in the flash flood analysis and prediction process (see Box 5.1).

more precise warnings. Flash Flood Watches and Warnings are typically provided for rainfall durations of 1, 3 and 6 h, and sometimes for 12 and 24 h (Box 8.2).

This technique has also been applied or evaluated in a number of other countries and regions (e.g. Norbiato et al. 2009; NOAA 2010). For example, in locations with sparse raingauge telemetry networks or no weather radar coverage, satellite precipitation measurements are widely used, supplemented and updated by raingauge estimates where these are available. For systems implemented within the World Meteorological Organisation (WMO) Global Flash Flood Guidance project, such as in Central America and southern Africa, a typical spatial scale for estimates of this type is 100–300 km^2 (e.g. NOAA 2010; De Coning and Poolman 2011). Probabilistic versions of this approach are also under development (e.g. Villarini et al. 2010). Internationally, some other approaches which have been evaluated and show potential include:

- Bayesian techniques combining information on rainfall and soil moisture and – when setting threshold values – taking account of stakeholder's attitudes and tolerance to risk using utility functions as part of a cost-loss approach (Martina et al. 2006; Martina and Todini 2009)
- Flash flood indicators – techniques which include a range of indicators of flash flood potential within the decision-making process, combining fixed catchment characteristics such as slope with antecedent conditions such as soil moisture and snow cover and real-time storm risks such as the speed of motion and rainfall intensity (e.g. Collier 2007; MacDougall et al. 2008)

As for rainfall thresholds, categorical statistics are widely used for evaluating the performance of flash flood guidance and related approaches. In some cases, these analyses are supported by extensive post-event field campaigns to determine which locations were flooded, whether an alert was received, the lead times provided if so, and the depth and extent of flooding (see Chap. 7). For example, in some parts of the USA, phone calls are routinely made to residents during or soon after heavy rainfall to gather information for subsequent use in forecast verification studies, including reports of false alarms (Gourley et al. 2010).

These types of analyses normally form part of routine and post-event reviews to identify areas for improvement and determine whether changes to threshold values are needed due to external factors. For example, as indicated in Table 8.2, in some countries reductions in river channel capacities are a serious issue due to catchment degradation and sedimentation, so that over time the severity of flooding tends to increase dramatically for given combinations of rainfall and soil moisture conditions. Structural interventions such as the construction of reservoirs and flood defences or levees can also affect the flood response and hence threshold values.

8.3.2 Site-Specific Warnings

To provide warnings at specific locations, threshold values based on river levels are widely used at locations with suitable river gauge observations. Some alternative names include criteria, triggers, alarms, and critical levels. Typically this approach is limited to locations where the typical rate of rise in levels is such that sufficient

Height (m)	Consequences
1.50	Water starts to break out of the Stopper River, flooding low-lying farmland to the south of Nevagazunda. Livestock and equipment need to be relocated to higher ground.
2.50	1 in 10 year flood level.
	The town common is flooded. This is a popular spot for campers during the summer months and during the annual Knee Knockers festival held in the last week of February. At the peak of the festival, up to 1000 tent sites may be occupied.
	Deck height of the old bridge over Kneys Creek. During flooding on the Stopper River, water can back up along Kneys Creek, closing this bridge and isolating up to 20 rural acreages east of Nevagazunda. During past flood events, access from these properties into town has been lost for up to one week.
3.50	The Nevagazunda Caravan Park is flooded. The van park has a normal occupancy of 50 people, but this can rise during peak periods to over 300. The park consists of 40 van sites, 10 of which are permanent, and 70 tent sites. Note: tent sites are located close to the river bank.

Fig. 8.6 Illustration of the first few lines in a flood intelligence record (Adapted from Australian Government 2009b. Reproduced with the kind permission of the Australian Government Attorney-General's Department)

time is provided for issuing warnings and, in a staged or phased flood warning system, these are typically preceded by general alerts or watches of the types described in the previous section. Thresholds are normally defined for gauges at or near the site(s) of interest, and sometimes supplemented by gauges further upstream (if available). For high risk locations such as city centres, these are often supplemented by on-site observations by trained observers in case of unexpected events, such as debris collecting at bridges or signs of potential flood defence failures.

When using a site-specific approach, as discussed in Chap. 6 the decision to issue a warning is typically made using action tables and maps showing which location(s) would be affected at a given gauge level. For example, Fig. 8.6 shows the first few lines from an example of a flood intelligence record presented in Australian Government (2009b).

When an upstream or 'remote' gauge is used, there is normally a trade-off between the additional lead time gained compared to the shorter lead time but greater accuracy provided by a nearby or 'at-site' gauge. In some cases, more complicated forms of threshold are defined based on river flows or observations at several gauges; for example, to allow for the influences of factors such as tributary inflows, flow control structures and tidal variations. These are typically expressed in the form of logical rules or multiple regressions or, more usually, as look up tables or charts. For high risk locations such as tidal barriers, extensive off-line hydrodynamic modelling studies are sometimes performed to develop this type of approach.

In many flood warning services, river gauge thresholds are a key decision-making tool. Typically for each gauge two or more thresholds are defined, corresponding to different stages of flood alert. For example, Fig. 8.7 illustrates the flood warning classifications used in Australia (Australian Government 2009a). These can be used as a general guide for response agencies and are defined as follows:

- Major Flooding. This causes inundation of large areas, isolating towns and cities. Major disruptions occur to road and rail links. Evacuation of many houses and business premises may be required. In rural areas widespread flooding of farmland is likely

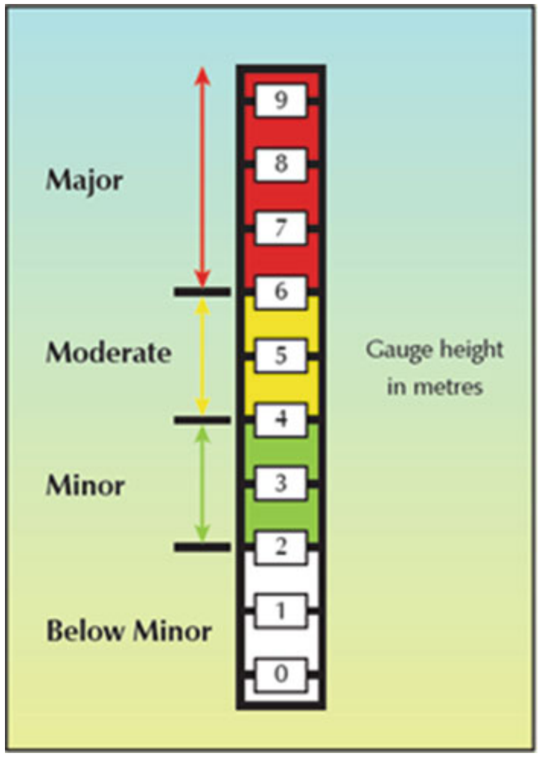


Fig. 8.7 Minor, Moderate and Major Flooding (Adapted from Australian Government 2009a. Reproduced with the kind permission of the Australian Government Attorney-General's Department)

- Moderate Flooding: This causes the inundation of low lying areas requiring the removal of stock and/or the evacuation of some houses. Main traffic bridges may be closed by floodwaters
- Minor Flooding: This causes inconvenience such as closing of minor roads and the submergence of low level bridges and makes the removal of pumps located adjacent to the river necessary

In some organisations, primary and backup gauges are designated for high risk locations to help guard against the risk of instrument or telemetry failure, and additional threshold values defined for key operational actions such as contacting critical infrastructure operators or closing flood gates. Backup or 'last-resort' alarms based on float or electronic switch-based level-detectors are sometimes also used, although with the risk that they might not operate when needed, or result in occasional false alarms (see Chap. 6).

For a regional or national flood warning service the number of threshold values required can be large and of the order of several hundred or more. Typically these are written into flood warning procedures (see Chap. 6) and managed using a telemetry or flood forecasting system, capable of providing alerts via emails, map-based displays and other methods (see Chaps. 3 and 5). However, paper-based manuals are normally kept as a backup in case of equipment failure. Where the decision-making criteria become more complex, decision support systems are increasingly used (see Chap. 6) although again simpler backup approaches are normally retained in case of software or hardware problems.

In some cases. completely automated warning systems are used in which the exceedance of a threshold activates a siren, barrier or other warning device. However, as discussed in Chaps. 1 and 6, due to the risk of false alarms, systems of this type tend to be used only in a limited number of situations, such as at low water river crossings and in some debris flow or dam break warning systems (see Chaps. 9–12). In recent years, another development has been the introduction of the option for users to define their own thresholds via a website in order to receive text message and other alerts when values are exceeded (e.g. see Box 3.1). These typically provide a useful complement to a more formal warning service although it is up to the user to decide how to make best use of the information provided. However as noted in Chap 6, in some countries the inclusion of more formal warnings with actions to take is being trialled for selected fast response catchments.

When thresholds are defined by a flood warning service, the values used are typically estimated based on experience from previous flood events and verification studies. For example, performance tests are usually based on long-term time series of river level data for the site(s) of interest, again using categorical statistics and measures such as the minimum, mean or median lead time provided (see Chap. 5). When a hydrodynamic model is available this can be used to explore how levels at river gauges relate to the onset of flooding at flood risk areas; however the accuracy of models is rarely sufficient for thresholds to be defined based on model outputs alone.

The resulting values should then be reviewed and updated at regular intervals, and particularly after major flood events. As for rainfall-based thresholds, some factors to consider include the possible influences of sedimentation and construction works, plus gauge-specific issues such as changes in datum values; for example if a gauge has been relocated or repaired following damage in a flood event. Generally, a compromise is needed between setting a threshold value low to extend the lead time, or using a higher value to reduce the number of false alarms, but with the risk of failing to issue a flood warning in time (or at all) when a flood occurs (e.g. USACE 1996 and Chap. 7).

In many cases, the values used are based on ideas about the typical rate of rise of river levels at a site and hence the likely lead time available before the onset of flooding. Thresholds based on observed levels are therefore normally set some way below the levels which correspond to the onset of flooding. Target lead times are typically agreed in consultation with civil protection authorities, emergency responders and community representatives, or defined nationally as part of a service level agreement. Where more than one gauge is used on the same river, assumptions are usually also required about the typical time of travel of flood waves between gauges.

These observation-based approaches might therefore be regarded as a simple empirical form of river level forecasting. However – particularly for flash floods – the advance warning which can be provided may be limited so, for greater accuracy and lead times, flood forecasting models are increasingly used. Typically these aim to provide information on the likely timing and magnitude of the flood peak, and sometimes on the duration and extent of flooding. To use model outputs operationally, this usually requires additional thresholds to be defined, which are sometimes called ‘forecast’ or ‘result’ thresholds. Due to the additional lead time provided, values are typically set at higher levels than for observations alone, such as the levels at which flows first go out of bank in a flood risk area, or for which off-line modelling studies suggest that flooding is likely to start at critical locations. However, if possible verification tests should be used to determine if these assumptions provide the required combination of lead times and accuracy and that false alarm rates are acceptable. Some options for integrating forecast thresholds into operational procedures include (Sene 2008):

- Issue the warning either if the observed value is exceeded, or if the forecast value is exceeded
- Issue the warning if both the observed and forecast values are exceeded
- Consider issuing the warning if the observed value is exceeded, using the forecast outputs to take (*or guide*) the final decision
- Generate warnings to individual properties or groups of properties from real-time forecasts of the inundation extent

For a given lead time, these approaches typically provide different combinations of ‘hit rates’ and false alarm rates and other possibilities could also be envisaged. They also rely on the forecasting model outputs to varying extents and it is only in the first and last cases that warnings could be issued solely on the basis of forecasts alone. In meteorological forecasting this is sometimes called a ‘warn-on-forecast’ approach (e.g. Stensrud et al. 2009). Due to the uncertainties in model outputs, a contingency is sometimes included via ‘soft’ and ‘hard’ limits, in which a duty officer has some flexibility in the decisions taken when the soft limit is exceeded, but must take specific actions once the hard limit is reached. More complex rules are also used in some cases, such as for locations affected by flow control structure operations, and are typically programmed into decision support systems (see later). There are also some specific factors to consider for real-time inundation mapping which are discussed in the following section.

In practice, the use of observation-based thresholds – either alone or in combination with forecasts – is therefore still central to many flood warning services, combined with rainfall threshold and other approaches (see Section 8.3.1 and Chap. 5). However, the choice of approach to use typically depends on a range of factors, including organisational policy, past performance using observations alone, gauge reliability and – in particular – the warning lead times ideally required and the confidence in model outputs at the lead times of interest based on forecast verification studies.

Another consideration is that, by using multimedia and other targeted warning dissemination systems (see Chap. 6), there is the option to set thresholds to meet the needs of individual users, such as critical infrastructure operators. Subject to technical feasibility, examples could include tuning thresholds to try to meet – on average over the long-term - user-specified minimum warning lead times or maximum acceptable false alarm rates for frequent flooding locations. There is also an increasing trend towards the use of probabilistic and ensemble approaches; for example by using probabilistic thresholds and decision criteria which consider the consistency (or persistence) between forecast model runs. This has the potential to provide a more risk-based approach to issuing warnings and this topic is discussed further in Chap. 12.

8.3.3 Flash Flood Forecasting Models

When flood forecasting models are used in the warning process, the main interest is usually to provide earlier indications of potential flooding than is possible from observations alone. The model outputs can also help with interpreting complex and fast-developing situations and event-specific factors such as debris blockages.

Before implementing a model, the outputs are often evaluated in pre-operational tests for at least 1–2 flood seasons. Typically the emphasis is on testing the performance using categorical statistics and key hydrograph characteristics for a range of lead times. A decision then needs to be taken on whether confidence in the outputs is high enough for the forecasts to be used operationally, and to what extent. For example would the outputs be used primarily for operational actions such as mobilising staff and informing civil protection agencies, or more directly to help in deciding whether to issue warnings to the public? Since the forecast uncertainty usually increases with lead time a maximum value may also need to be specified, beyond which outputs are not to be used, or are for guidance only. Typically this limit would again be determined by forecast verification studies of the types described in Chap. 5.

The types of model which are used range from simple approaches such as correlations or rate-of-rise (extrapolation) triggers to integrated catchment models combining rainfall-runoff and hydrological and/or hydraulic flow routing components. The background to these approaches is discussed in Chap. 5 together with some criteria for the choice of model. Typically these include factors such as the level of risk, past experience with particular models, catchment response times, the required warning lead time, data availability, and cost.

For flood forecasting on large rivers, the current state-of-the-art approach is typically to use an integrated catchment model with ensemble rainfall forecast inputs, multiple rainfall-runoff models, and a real-time hydrodynamic component (e.g. see Box 8.3). Data assimilation is normally used at all gauges where the observations are sufficiently reliable, with estimates of the uncertainty in outputs provided at all lead times of interest (see Chap. 12). Additional modelling components are included as required; for example, for snowmelt and reservoir operations.

Simpler chart or look-up table based models are also widely used in parallel with these more complex types, both as a backup and as a 'reality-check' on the outputs, with paper-based copies kept in reserve in case of complete failure of the forecasting system. Approaches of this type are also widely used in community-based flood warning systems (e.g. FEMA 2006).

For flash flood applications, a similar approach is generally used although, due to the rapid response to rainfall, the emphasis tends to be more on rainfall-runoff models. However, flow routing components are often included where there are telemetered river gauges upstream of the location(s) of interest. This usually provides more accurate forecasts, although at shorter lead times. For example, Fig. 8.14 provides an illustration of the trade-off between lead time and forecast accuracy for these different modelling approaches. Data assimilation is again widely used to improve model performance.

When a hydrodynamic component is included, real-time inundation maps could potentially be generated as a guide to issuing flood warnings, including estimates for the flooding extent, depths and velocities. However, this approach is not widely used at present and pre-defined maps tend to be favoured. This is partly due to model run-time and accuracy considerations (see Chap. 5) and because this provides the opportunity to check and audit maps off-line before they are used operationally. Maps are typically presented either as a series of paper-based printouts corresponding to different river gauge levels, or within a GIS-based viewer or decision support system (see Chaps. 6 and 7 and Box 1.1). However a real-time mapping model has the potential to take account of event-specific factors and run times continue to reduce due to faster computer processors and more efficient algorithms. This approach is therefore likely to be used more often in future.

An additional challenge – which is particularly relevant to flash flood applications – is providing operationally useful forecasts for ungauged locations; that is, in catchments which do not have a telemetered river level gauge at or near the locations where site-specific warnings are required. In addition to the rainfall threshold and flash flood guidance approaches discussed earlier, real-time distributed physical-conceptual models are increasingly used in this situation. This approach is described in Chap. 5 but in summary models typically operate on a gridded basis with rainfall forecast and/or weather radar or raingauge-based inputs and a cell-to-cell flow routing component. As in flash flood guidance approaches, the threshold values for flooding are often defined in flood frequency terms, such as the 1 in 2 or 1 in 5 year flood. Variational, Kalman filter and other data assimilation techniques are also increasingly used based on observations at any river gauges within the domain of the model. Compared to simpler techniques, this approach has the advantage of providing quantitative estimates of flooding severity and is increasingly used both for issuing medium- to long-range advisories in probabilistic terms and for shorter-range flash flood alerts in ungauged catchments.

8.4 Catchment-Specific Factors

8.4.1 Introduction

In a river catchment, there can be many local factors to consider which affect the flow response. Often, these are only apparent at low to moderate flows but in some cases there are significant influences on flood flows.

One common example is the influence of operations at flow control structures and reservoirs. Typically the main effect is to attenuate and delay flows and possibly to introduce unusual patterns into the flow response, such as sudden increases,

Fig. 8.8 Illustration of river flows in the Kamp catchment downstream of the Dobra reservoir. *Left*: dry channel during below average inflow into the reservoir. *Right*: flow during a flood when the spillway of the dam was in operation (Blöschl 2008). (Reprinted by permission of Taylor & Francis Ltd., http://www.informaworld.com)

drops or cyclical behavior. However, during high flow conditions there is a risk that reservoirs will spill or overtop, or that control structures will need to be fully opened (or closed), leading to an increased risk of flooding at other locations (e.g. Fig. 8.8). Event-specific factors such as debris blockages and ice jams can also occur, raising levels and hence the flood risk immediately upstream, and leading to flooding at locations further downstream if the blockage suddenly clears.

To provide an illustration of the methods used, the following sections consider a range of monitoring, forecasting and warning techniques for two particular situations: ice jams and reservoir and flow control structure operations. More generally, for reservoirs and structures, there is often a requirement to consider other forecasting applications such as for irrigation, water supply, navigation, hydropower operations and pollution control. Although these topics are not considered here, from a flooding perspective it is worth noting that the wider user base can potentially help with the sustainability and funding for a flood warning system. Also, in locations where there is a distinct flood season (or seasons), year-round operations often help to maintain staff skills and ensure that telemetry and other equipment continues to operate.

8.4.2 Ice Jams

In colder climates, ice jams present a recurring risk at some locations, sometimes forming several times a year on the same river (although not necessarily always resulting in flooding). Blockages typically occur when river ice breaks up and accumulates at locations such as sharp bends and obstacles such as bridge piers (e.g. Snorrason et al. 2000; Beltaos 1995, 2008). Most ice jams – or ‘break-up jams’ – form following rapid increases in river flow, lifting and breaking up river ice, although thermal effects sometimes play a role; for example from increasing air temperatures, solar radiation or discharges of waste water into rivers. Freeze-up jams also occur when ice accumulates at the upstream end of an iced-over river reach but usually present less of a flood risk.

Some locations which are frequently affected by ice jam floods include the USA, Canada, Iceland, Russia and Scandinavia. In addition to the risks from increased levels upstream – or downstream if the ice jam suddenly clears – other risks to people can arise from floating ice in flood waters and hypothermia. Ice jam events are one of the fastest-developing types of flash flood with times of minutes to an hour widely reported between the initial blockage and widespread flooding. In some cases, longer term flooding issues arise if air temperatures drop and an ice jam freezes in place for a few days or weeks. In this situation, some options for removing the blockage include excavation and blasting. More generally, some techniques which are used to reduce or break up river ice upstream of locations at risk include ice booms, drilling, cutting, and changing dam and river discharge consents to increase flows and/or water temperatures. More permanent solutions to flooding problems include levees, flow diversion channels and ice retention piers and structures.

Where there are known locations at risk, additional monitoring is typically performed during the winter months and flood response plans updated. In some cases, hydraulic models are used to assess the likely extent of flooding for different heights of blockage. For example, several one- and two-dimensional modelling packages include an ice jam modelling capability (e.g. Morse and Hicks 2005). Compared to river modelling (see Chap. 5), some additional inputs required typically include parameters such as the extent of the ice jam, the relative areas of open water and ice cover, the thickness and roughness coefficient for the ice cover and the underside of the ice jam, and an internal friction parameter relating to the ice jam rubble. An allowance is sometimes also included for the influence of floating ice on flows, and a threshold velocity under the ice jam specified, beyond which the jam would no longer be stable. In real-time operation, models of this type could potentially be applied on a daily basis (or more frequently) to update estimates of flood risk based on observations of ice jam formation (e.g. Tang and Beltaos 2008). A database of previous ice jam events is another useful tool to assist with deciding on the potential risk and possible mitigation measures (White 2003).

Some typical monitoring techniques include still or video cameras and additional river level gauges to detect sudden rises in levels upstream of known blockage sites. Rate of river rise and overbank threshold values are then typically defined for use in alerting emergency response staff (e.g. Williams and White 2003). Early warnings or advisories are sometimes also issued on the basis of short-range weather forecasts and flood forecasting model outputs; for example for rising air temperatures and/or observations or forecasts of rapidly increasing river levels or flows. In areas where river ice forms, temporary ice motion detectors provide one option for monitoring ice break up, such as trip wires drilled into the ice and connected to a

Fig. 8.9 Ice jam in Montpelier, Vermont, 1992 (USACE 2009)

voltage supply and a modem for telemetry. Water temperature observations provide another option for indicating the potential risk. Satellite imagery is also widely used to provide a more general assessment of ice cover and Synthetic Aperture Radar (SAR) observations help to avoid visibility problems during cloud cover. Regular aerial surveys are also used in some locations, such as in the RiverWatch program in Alaska (NOAA/NWS 2012). Reports from observers and volunteer spotters provide another useful source of information, and in some locations (e.g. parts of the USA) are made available on map-based websites.

As the risk of an ice jam increases, there may also be time to take preparatory actions before problems occur. For example, during the winter of 2007, river ice conditions raised the possibility of a repeat of the Montpellier ice jam flood noted in Table 8.1 and illustrated in Fig. 8.9. A multi-agency group was established including the city authorities, the National Weather Service, FEMA and a number of other agencies (FEMA 2008). Additional river gauges were installed and the river ice thickness and channel widths monitored, with attempts made to reduce the ice cover by methods such as pumping warmer water into the river and diverting a wastewater outlet to a location further upstream. Other precautions included stockpiling sandbags and distributing evacuation maps, and some businesses moved stock from basements and low-lying areas. In this instance, there was no ice jam related flooding but one conclusion was that the procedures used could usefully be applied in future years, and at other ice jam prone locations.

Although it would be desirable to forecast the formation and break up of ice jams, due to the complexities of the processes involved forecasting techniques are little used at present. Perhaps the most well established methods are in the related area of forecasting the formation of river ice, for which empirical techniques are widely used relating ice formation to air temperature and other factors. More physically-based approaches have also been developed using hydraulic and energy balance models (e.g. Kubat et al. 2005).

Fig. 8.10 Some examples of hydraulic structures. From *top left clockwise*: flow control barrage, flood defence scheme, culvert exit, arch dam

Modelling river ice break-up and ice jam formation processes is more challenging since a range of mechanical, thermal and other effects need to be considered, and there are few comprehensive datasets available for model calibration and validation. However, some techniques which have been evaluated and show potential include multivariate statistical methods and artificial neural networks (e.g. White 2003; Mahabir et al. 2006). There is also much active research on the development of process-based models combining hydraulic and ice modelling components and these often provide promising results when suitable calibration datasets are available (e.g. Carson et al. 2011).

8.4.3 Reservoir and Flow Control Structure Operations

Rivers often contain a range of structures for flow regulation, flow diversion, and other purposes (e.g. Fig. 8.10). Some typical applications include flood control, irrigation, navigation, hydropower generation, river gauging and water supply and examples include weirs, sluices, gates, tidal barriers and siphons. Off-line structures such as washlands and flood detention reservoirs are also used for irrigation, flood control and other purposes. On a larger scale, reservoirs are often used for multipurpose applications such as water supply, hydropower, irrigation and recreation. During

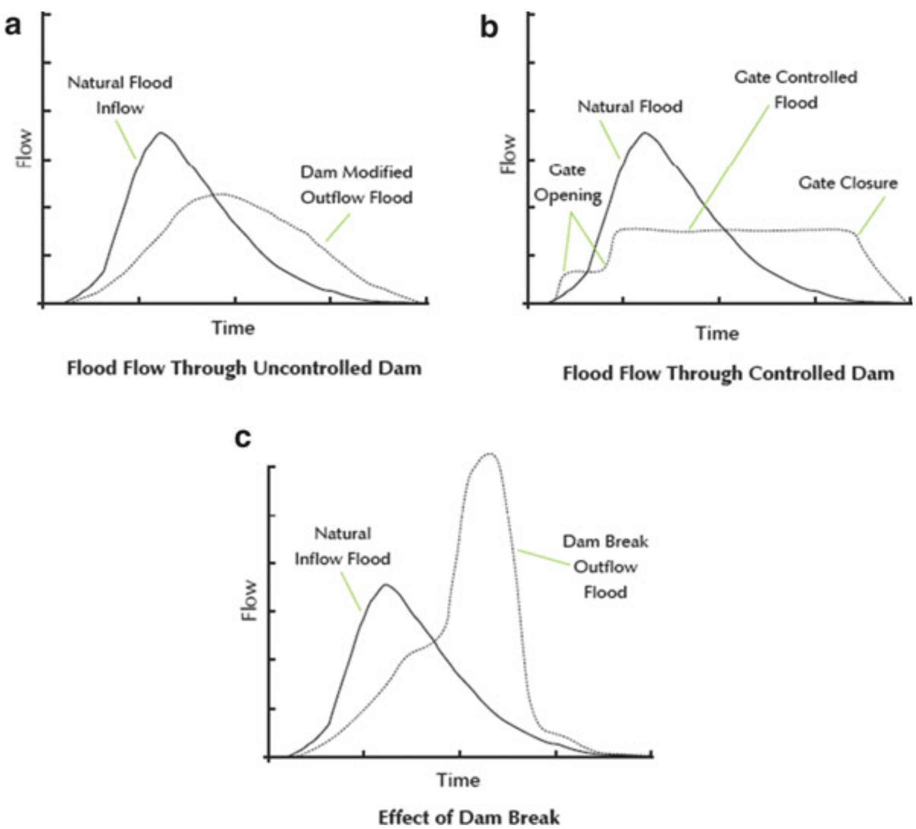


Fig. 8.11 Flood-Handling Effects of Dams (Australian Government 2009c). (Reproduced with the kind permission of the Australian Government Attorney-General's Department)

flood conditions, other structures such as bridges (road, rail, pipeline) and culverts sometimes affect levels and flows at locations further upstream and/or downstream; for example, if water reaches or overtops a bridge deck, or a culvert surcharges.

In some cases structures are controllable, either based on an operator's inputs on site or via a telemetry system, or moving automatically following a pre-defined set of control rules. These operations have the potential to cause significant changes to river levels and/or flows at a flood risk area; however the effects need to be considered on a case-by-case basis. For example, if a reservoir has spare capacity or is drawn down so as to provide a buffer for flood storage, this usually significantly delays and attenuates flows further downstream (e.g. Fig. 8.11). By contrast, if a reservoir spills, this can cause a significant increase in flows at locations downstream with the risk, in extreme cases, of the spillway capacity being exceeded, leading to overtopping of the dam crest and potentially a dam break (see Chap. 11). On a lesser scale, similar considerations apply to river flow control structures. For example, upstream levels are often raised by gate closures at a barrage or tidal barrier, potentially leading to flooding in those areas, whilst opening sluices and other gates during floods to protect the structure potentially adds to the flood risk further downstream.

For a reservoir, some key operational factors to consider during a flood event typically include the risk of overtopping of the dam walls, the current flood buffer for storing flood flows (and whether further draw-down is needed), the likelihood of multiple flood peaks during a succession of storms, and the extent and types of warning to issue. Additional complications arise in multiple-reservoir systems, where the fill and draw-down sequence needs to be considered throughout the system.

The optimum response strategy is often developed with the aid of models and many techniques are potentially available (e.g. Chanson 2004; Chow 1959; Novak et al. 2006). For example, for a reservoir, exploratory calculations may show that a simple hydrological routing approach is sufficient to represent the attenuation and time delay between inflows and outflows, or that the impacts are small enough to be neglected. However, if required, more precise estimates of reservoir levels and spillway flows could be obtained using a hydrodynamic model based on bathymetric survey data for the reservoir and design drawings for the spillway and the outflow (tailwater) channel.

For real-time forecasting similar approaches are used, with inflows estimated from catchment models of the types described in Chap. 5. These are then used as inputs to a water balance, hydrological routing or hydrodynamic model, taking account of water levels, spills and releases and – if significant – direct rainfall and evaporation at the reservoir surface. Ideally telemetered values for the reservoir levels, spillway flows, control structure settings (if any), and inflows would be available to support operation of the model; however in many cases these are not available which frequently places some limitations on the choice of approach.

Similar approaches are used for flow control structures and, in urban areas, real-time models often include representations of all significant structures which are likely to influence river levels and flows. Tidal influences sometimes also need to be considered and are typically represented either using look up tables or charts or hydrodynamic models. For example, Huband and Sene (2005) describe development of a real-time hydrodynamic model for flood forecasting, drought, water supply, navigation and other applications at 52 forecasting points. The original version included 55 lumped conceptual rainfall runoff models and more than 400 km of hydrodynamic model network, with almost 500 structures including flood storage reservoirs, siphons, pumps, gates, bridges, weirs and culverts.

Where structures are controllable, the operating rules used typically range from simple rule-of-thumb, chart-based or tabulated procedures based on experience or modelling to complex logical rules which need to be encapsulated in a hydrodynamic model or decision support system. The level of detail used is typically linked both to the flood risk and the consequences of failure at a structure. However, the rules used in practice may differ considerably from the design rules for a range of technical, economic, or political reasons, requiring additional consultations and exploratory modelling. Another consideration is that, during flood conditions, structures such as lock gates and sluices are sometimes fully opened or closed, or control is lost at weirs and other locations due to critical levels being exceeded.

For larger dams and structures, it is usually desirable to optimize the control rules to reduce operating costs and risk, and balance competing objectives. This is particularly the case for multi-purpose reservoirs with a range of applications, such as water supply, irrigation, hydropower generation and recreation. For flood control, one particular consideration is the cost (or opportunity loss) of releasing water to free up flood storage versus the risks of flooding at locations further downstream. Some examples of the optimization techniques which are used include long-term simulation modelling and linear or dynamic programming, using observed, synthetic or stochastic representations of the inflows (e.g. Yeh 1985; Wurbs 1992; Labadie 2004; Nandalal and Bogardi 2007). Separate short-term or emergency operating rules are often also required for use in flood conditions (e.g. Nandalal and Bogardi 2007).

For flood warning applications, some examples of the types of thresholds which are used include the rate-of-rise of levels, current levels, and values for the water levels or flows immediately upstream and downstream of a structure. In some cases these are included in decision support tools to assist with real-time operations and for off-line applications such as operator training and emergency response exercises (e.g. Fritz et al. 2002; Guo et al. 2004). As discussed in Chap. 12, probabilistic approaches also have the potential to assist with optimizing real-time operations and reducing operating costs and opportunity losses, and this type of approach has been used (or evaluated) in a number of flood-related applications.

However, in all cases, the operating rules need to remain flexible enough to be adapted if event-specific issues occur; for example, a rapid drawdown of levels might be required if problems such as seepage or erosion arise at a dam wall or if overtopping seems a possibility. There is also a risk that telemetry and communication systems and gates and other control structures will fail. Operators are sometimes also faced with difficult decisions such as whether to release water to free up flood storage based on an inflow forecast which might be wrong, when this could possibly exacerbate minor flooding already occurring downstream. However, to some extent, the risks from these and other factors can be reduced if the possibility had already been foreseen and contingency plans developed, and Chaps. 7 and 11 discuss this topic further.

Box 8.3 Flash Flood Forecasting System, Kamp Catchment

The river Kamp is situated in northern Austria and has a catchment area of 1,550 km^2 (Fig. 8.12). Elevations range from 300 to 1,000 m and the mean annual rainfall is approximately 900 mm. The geology is primarily granite and gneiss although with extensive areas of sandy soils. Floods can arise from frontal storms bringing moist air from the Mediterranean and from thunderstorm, snowmelt and rain-on-snow events.

The response time between rainfall and flood flows is about 6 h at the downstream end of the catchment. However the response is affected by three reservoirs in the central reaches: the Ottenstein, Dobra and Thurnberg. These have an active storage capacity of about 72 million cubic metres and are used for hydropower generation, recreation and flood control. The sandy soils also result in unusually low flows for much of the year compared to

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Box 8.3 (continued)

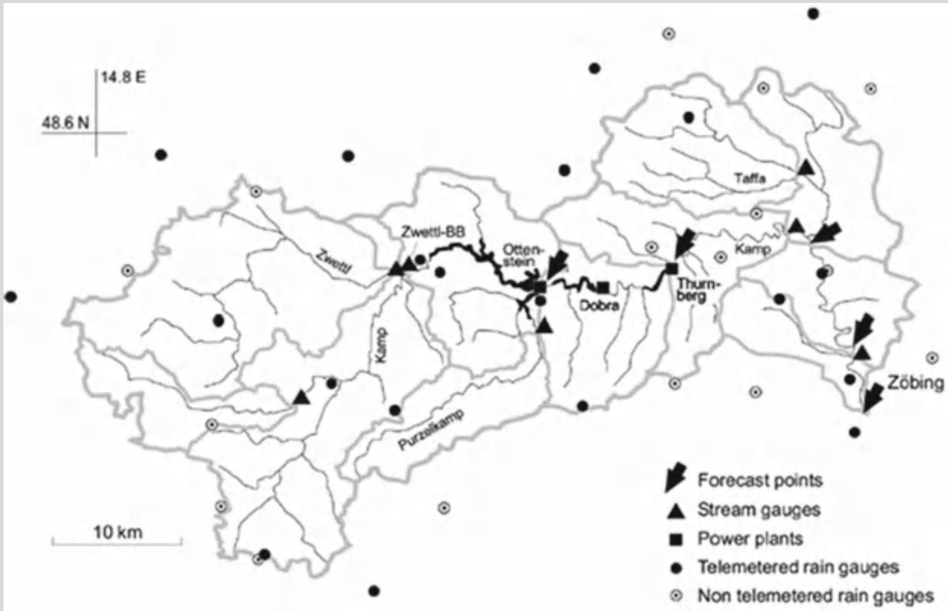

Fig. 8.12 The Kamp catchment with data network, hydropower scheme (*squares*) and forecast points shown. *Thick grey lines* and *thin black lines* represent the catchment boundaries and the river network respectively (Blöschl 2008). (Reprinted by permission of Taylor & Francis Ltd., http://www.informaworld.com)

other catchments of a similar size elsewhere in Austria, but a rapid response to heavy rainfall once soils are saturated.

Since 2006, a distributed physical-conceptual rainfall-runoff model has been used operationally for flood forecasting in the catchment. This was developed by the Institute for Hydraulic and Water Resources Engineering at the Vienna University of Technology, with support from the State Government of Lower Austria and the EVN Hydropower Company in Austria.

The catchment is represented by 13 subcatchments, 10 hydrological routing reaches and three reservoir modules, together with a snowmelt component (Reszler et al. 2007; Blöschl et al. 2008). The model runs at a time step of 15 min on a 1 km grid. An ensemble Kalman Filter approach is used to update the initial soil moisture storage in the model based on the forecast errors at the telemetered river gauges; this is also combined with an autoregressive error prediction approach at each gauge (Komma et al. 2008; Blöschl et al. 2008). For this catchment, updating of antecedent soil moisture

(continued)

Box 8.3 (continued)

conditions is particularly important to provide more accurate initial conditions as flood events develop.

The main meteorological inputs are weather radar and raingauge observations and ensemble precipitation and air temperature forecasts downscaled to the model grid scale. The forecasts are provided by the Austrian Meteorological Office (ZAMG) and combine advection-based nowcasts at shorter lead times and Numerical Weather Prediction (NWP) model outputs at longer lead times. For the NWP outputs a weighted ensemble is used from the ALADIN local area model (10 km, hourly outputs) and European Centre for Medium-Range Weather Forecasts (ECMWF) model (22 km, 6 hourly outputs). Analyses of forecast performance suggest that the nowcasting approach has smaller errors over the first 2–6 h of the forecast but that the NWP outputs are more accurate at longer lead times.

During the initial model calibration and verification process, spatially distributed observations were used in addition to rainfall and flow data from individual gauges. This included information on groundwater levels, soil moisture, soil waterlogging, snow cover and flood inundation levels. The model parameters were optimised selectively according to the dominant physical processes during low flow periods and for a range of types of flood event, such as those driven by convective rainfall, snowmelt and rain-on-snow. River channel survey, wrack marks and anecdotal evidence of flow paths and inundation extents were also used in calibrating the routing component, together with the outputs from one- and two-dimensional hydrodynamic models.

One particular challenge was to decide how to represent the reservoir operating rules since these can have a considerable impact on the flows downstream. Discussions with the operators showed that releases are typically made on a case-by-case basis, taking account of forecast inflows, electricity prices and other factors, whilst maintaining reservoir levels and discharges within agreed minimum and maximum values. For example, as flood events develop, there is often a trade-off between the risk of releasing flows unnecessarily to provide additional flood storage and the potential consequences of flooding further downstream.

To develop the reservoir component of the model, a multi-agency team was therefore established to discuss, review and update the operating rules used in the model (Fig. 8.13). The input from the reservoir operators was essential and the process itself also increased the confidence of staff in the model, and provided useful training in the meteorological and hydrological factors to consider during extreme flood events.

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Box 8.3 (continued)

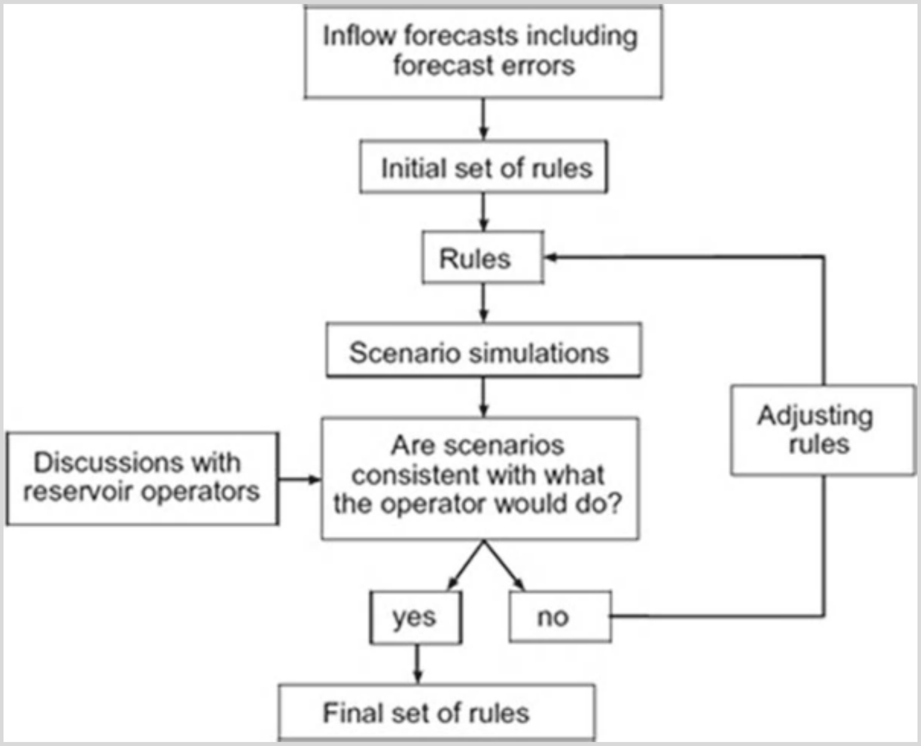

Fig. 8.13 Iterative procedure for developing the reservoir simulation model based on the judgement of the reservoir operators (Blöschl 2008). (Reprinted by permission of Taylor & Francis Ltd., http://www.informaworld.com)

Figure 8.14 shows a schematic assessment of the accuracy of the flow routing and rainfall-runoff components of the model when used for real-time forecasting. An example of an ensemble runoff forecast is also shown for a gauge in the upper reaches of the catchment, upstream of the first reservoir. As expected, the highest accuracy arises for short lead times when the flow routing component of the model dominates the outputs, whilst the accuracy is least at lead times for which rainfall forecasts are the primary input.

In practice, therefore, flood warnings are issued for lead times when the routing component dominates, with pre-warnings and early warnings issued at longer lead times. The inputs from forecasting staff are also vital in the warning process in evaluating the accuracy of forecasts and identifying unusual and extreme situations as they develop (Blöschl 2008). Forecasts can then be adjusted to take account of model errors and event-specific factors, such as departures from the assumed reservoir operating rules.

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Box 8.3 (continued)

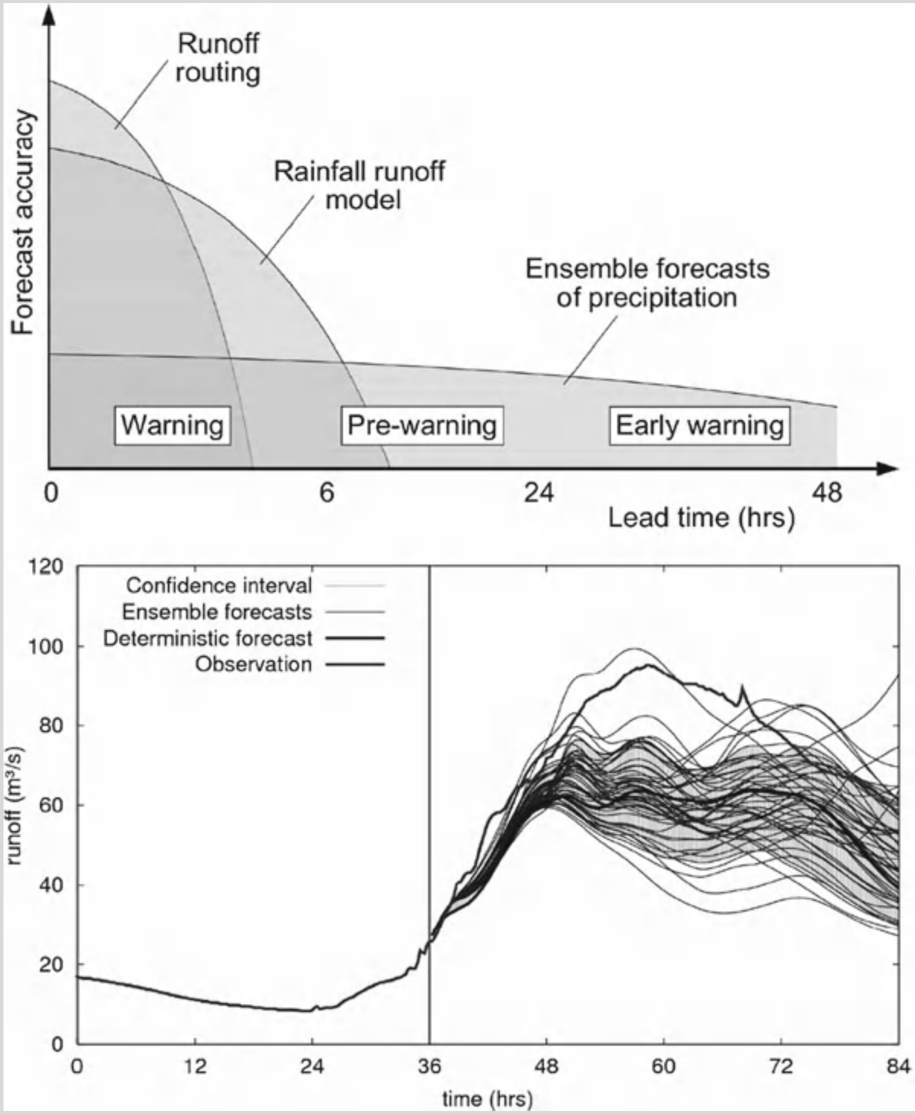

Fig. 8.14 Illustration of the accuracy of the main components in the Kamp model at different lead times and how these correspond to the warnings which are issued, and an example of ensemble flow forecasts for the Kamp at Zwettl for a forecast time of 12:00 on 10 July 2005 (Komma et al. 2007; Blöschl 2008). (Reprinted by permission of Taylor & Francis Ltd., http://www.informaworld.com)

8.5 Summary

- For rivers, the flood risk is typically assessed using a combination of hydrological and hydrodynamic models, flood chronologies and anecdotal information. In particular, the development of LiDAR and other high-resolution digital terrain survey techniques has transformed the accuracy of model-based estimates in recent years, such that this is now the preferred approach where suitable calibration datasets are available. Typically unit hydrograph techniques are used to estimate inflows combined with one- and two-dimensional models of the river network and floodplain

- However, for flash floods, due to data limitations or cost, simpler approaches are sometimes used to assess risk, at least for an initial regional assessment. Typically these relate flood magnitudes to catchment characteristics such as slope, soil types, forest cover and land use. Other factors are sometimes considered, such as catchment response times and the risk of snowmelt or debris blockages
- Rainfall depth-duration thresholds are widely used to provide an initial general alert, watch or early warning in the early stages of a possible flood event, although with many uncertainties about the likely locations, timing and magnitude of flooding. Typically real-time observations are obtained from raingauges or weather radar and rainfall forecasts are used in some systems. Flash Flood Guidance techniques are also widely used and consider soil moisture conditions as well. Where suitable raingauge or weather radar observations are unavailable, satellite precipitation estimates are widely used as a substitute
- When river gauge telemetry information is available, in some cases this allows site-specific warnings to be issued for individual communities at risk from flooding. Both single site and multi-criteria thresholds are used and the performance of the overall warning system is strongly dependent on the values chosen. Regular performance reviews are therefore required; for example in terms of lead times, the probability of detection and false alarm ratios. For a national or regional warning system there are often many threshold values to manage and typically this is done using a telemetry or flood forecasting system backed up by paper-based procedures
- Flood forecasting models are increasingly used as part of the warning process to help with decision-making and issuing warnings earlier than is possible from observations alone. Typically these combine rainfall-runoff and hydrological or hydrodynamic flow routing models for specific locations. Real-time distributed physical-conceptual models are also increasingly used operationally both for medium to long-range probabilistic flood forecasts and to help with issuing shorter-range flash flood warnings in ungauged catchments
- In colder climates, ice jams are another potential cause of flash floods but it is usually a challenge to predict the onset of flooding. However, where there are known locations which regularly cause blockages, such as at bridges in urban areas, the flood risk can be estimated from modelling studies, flood response plans prepared, and river level, camera and other instrumentation installed. However, due to the complex processes involved, forecasting techniques are little used operationally although the development of process-based and data-driven techniques is an active area for research

- Operations at reservoirs and river flow control structures sometimes affect the magnitude and timing of flash floods, and a wide range of forecasting techniques is available. In high risk locations, real-time hydrodynamic models are increasingly used, although empirical relationships and simpler flow routing methods are sufficient in some applications. One of the key challenges is often to represent the operating rules which are used in practice, requiring exploratory modelling studies and extensive consultations with operators

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Chapter 9
Debris Flows

Abstract Debris flows are a common occurrence in mountain areas and often cause widespread damage. Warning systems provide one approach to reducing the risk to people and property and usually rely on real-time monitoring of rainfall and ground conditions. Some options for instrumentation include raingauges, weather radar and ultrasonic or radar level sensors, and more specialized techniques such as geophones, pore pressure sensors and trip wires. Rainfall forecasts are also increasingly used to help to extend warning lead times. This chapter provides an introduction to these techniques and to the main approaches used for estimating the hazards from debris flows.

Keywords Debris flows • Early warning systems • Hazard mapping • Risk assessments • Monitoring • Forecasting • Thresholds • Wildfires

9.1 Introduction

Debris flows have many similarities to flash floods in rivers and the two types often occur together in mountain regions. However debris flows are characterized by high concentrations of mud, stone, rock and other types of material which pose an additional risk. For example, Iverson (1997) notes that the largest flows can transport boulders 10 m or more in diameter and have peak flow speeds exceeding 10 m s^{-1}. The deposits left after an event also lead to additional recovery costs and in some cases permanently alter the paths of watercourses.

One of the main causes of debris flows is heavy rainfall; for example from prolonged frontal rainfall, intense thunderstorms and land-falling tropical cyclones. Flows typically arise on steep slopes from areas of saturated (or near saturated) soils, sediment or fractured rock, and some potential contributing factors include deforestation, loss of vegetation, wildfires, road cuttings, and unsustainable farming practices.

However, as in all areas of flood risk management, the resulting flows only constitute a risk when they impact on people, property or infrastructure. Some particularly

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Table 9.1 Some examples of major debris flow events

Location	Year	Impacts	Cause
USA	1982	Extensive landslides and floods throughout the San Francisco Bay area. Many of the slides transformed into debris flows resulting in damage to at least 100 homes and causing 15 fatalities (U.S. Geological Survey 1988)	A rainstorm in central California dropped as much as half the mean annual precipitation within a period of about 32 h, with rainfall exceeding 400 mm in some locations
Venezuela	1999	Debris flows and flash floods occurred in about 24 streams in the northern coastal mountain range with thousands of fatalities and many towns devastated along a 50 km section of the coastal zone (Lopez and Courtel 2008)	14 days of heavy rainfall led to saturated soils, followed by up to 900 mm of rainfall in 3 days
Japan	1999	In Hiroshima city, more than 300 debris flows and slope failures resulted in 31 fatalities, one person missing and 154 houses completely destroyed (MLIT 2007)	Localised rainfall reached 60–80 mm h^{-1} or more in places with daily totals exceeding 200 mm in places
Switzerland	2005	Severe floods occurred along the northern side of the Alps in Switzerland including many debris flows, causing major economic damages (Rickenmann and Koschni 2010)	Three days of almost continuous rainfall with amounts exceeding 200 mm in 72 h in some locations
Taiwan	2009	Widespread flash flooding and debris flows in southern Taiwan resulted in more than 700 fatalities and damages exceeding $500 million (Chien and Kuo 2011)	A slow-moving typhoon (Morakot) resulting in daily rainfall of up to 1,200 mm in some places and some 4-day totals exceeding 3,000 mm
China	2010	Two debris-flows in Gansu Province in northwestern China resulted in 1765 fatalities and destruction of more than 5500 properties. The formation and subsequent failure of a debris-dam on a river further downstream was a significant factor and caused severe flooding in the city of Zhouqu (Tang et al. 2011)	Intense localized rainfall with a peak recorded hourly value of 77.3 mm

high risk locations therefore tend to include communities in mountain valleys and at the foot of coastal mountain ranges, and road and rail routes in these areas. Table 9.1 presents some examples of major events, although it is worth noting that debris flows can also arise from other causes, such as dam breaks and outburst floods (see Chap. 11), earthquakes and the melting of snow and ice by volcanic lava flows. However these non-meteorological causes are not considered here. Landslides resulting from heavy rainfall are also excluded although the general approach used for risk assessment is similar (see, for example, Fell et al. 2008).

Some approaches to reducing the risk from debris flows include non-structural measures such as development control (zoning) and early warning systems, and a range of engineering interventions. For example, structural options include erosion control and slope stabilization works in headwater catchments, the use of sediment control or check dams along watercourse paths, and river channel improvements and defences in communities and at road and rail crossings.

However, early warning often has a high priority due to the many uncertainties in estimating which specific areas are at risk, and the potential costs of providing structural measures at numerous locations. For example, in Japan, there are estimated to be some 200,000 dangerous valleys and slopes with a debris flow or slope failure risk (Osanai et al. 2010). With sufficient lead time, some actions which can be taken on receipt of an early warning include evacuation of areas at risk, closing roads, and moving vehicles and valuable items to places of safety. However, due to the speed and erosive power of debris flows, there tend to be fewer options for protecting properties than for river flooding (such as the use of sandbags and demountable defences).

As for other types of flash flood (see Chaps. 2–7), the main items in an early warning system typically include monitoring, forecasting, and warning components, supported by a range of emergency planning (or 'preparedness') activities between events, such as developing response plans and emergency response exercises. Many of these techniques are suitable for debris flow warning systems; however there are also some key differences and this chapter highlights some of the main areas. The discussion begins with a brief review of how debris flows are defined and of models for flow initiation and transport. Monitoring and forecasting techniques are then discussed, and in particular the use of rainfall thresholds to help to decide whether to issue warnings.

More generally, some guidelines on debris flow risk assessment and mitigation include examples from Japan (Ministry of Construction 1999; MLIT 2007), Australia (Australian Government 2001) and internationally (World Meteorological Organisation 2011). In some cases these include a discussion of related topics such as evacuation procedures and the post-event recovery phase. As for other types of flash flood, most also emphasise that – for a warning system to be effective – all components must operate effectively together and communities must be fully engaged in the design and operation of the system. Box 9.1 also describes an operational system which illustrates many of the latest developments in debris flow warning systems, for the particular case of flows in wildfire damaged areas.

Box 9.1 Post-fire Debris Flow Warning System, Southern California

Wildfires frequently occur in southern California during the dry season months of May to November, leaving soils with little protection from vegetation. This increases the risk of debris flows, particularly in the first year or two following the event, following which vegetation starts to become re-established. Notable debris flows linked to burned areas have included multiple events during the winter of 1997–1998, the New Year's Eve storm of 1933–1934 during which up to 50 people were killed, the Christmas Day storm of 2003 which resulted

(continued)

Box 9.1 (continued)

in 16 fatalities, and a storm on 6 February 2010 that damaged 52 homes (NOAA-USGS 2005; Cannon et al. 2011).

Post-fire debris flows are most frequently generated through the progressive erosion and entrainment of sediment by runoff during heavy rainfall and can be caused by both convective rainfall events and more prolonged winter rainfall (Cannon and Gartner 2005). Events can sometimes also develop almost instantaneously in response to short periods of rainfall (Kean et al. 2011). Typically flows originate in basins with areas of up to about 25 km^2 with mean gradients of at least 15–20%. Antecedent rainfall amounts and soil moisture conditions are generally less of a factor than in undisturbed settings.

To provide early warnings of potential flows, a prototype debris flow warning system has been developed by the U.S. Geological Survey (USGS) in collaboration with the NOAA/National Weather Service (NWS) (NOAA-USGS 2005; Restrepo et al. 2008). This has been in operation since September 2005 and provides warnings for locations which have experienced wildfires in the previous 2 years.

A set of rainfall intensity-duration thresholds provide the basis for the approach, and studies in California and Colorado have shown that rainfall threshold values are typically much lower in burned areas than undisturbed areas. For example, debris flows can sometimes be generated in response to rainfall with return periods of only 1 in 2 years or less or – as a rough indication – for rainfall intensities exceeding about 10 mm h^{-1}. However, threshold values start returning to normal following a year of vegetative recovery and sediment removal (Cannon et al. 2008, 2011). Separate threshold values are therefore defined for the first and second rainfall seasons following a wildfire. For operational use, a risk-based approach to decision-making has been developed in which four categories of threshold are used (e.g. Fig. 9.1). These are based on observations from previous events of factors such as total debris volumes, the number of drainage basins affected in the burned area and the impacts on properties, roads, bridges and drainage networks (Cannon et al. 2011).

The resulting thresholds are integrated into the flash flood warning system operated by the Los Angeles-Oxnard and San Diego Weather Forecast Offices. In real-time operation, locations where threshold values are exceeded are identified using the NWS Flash Flood Monitoring and Prediction (FFMP) tool. This map-based system processes and displays rainfall measurements and forecasts on a gridded basis and accumulates values to a basin scale over a range of durations. The outputs are one of the criteria used by forecasters when deciding whether to issue warnings, alongside other information such as numerical weather prediction model outputs and spotter reports.

When issuing warnings, the same alert and warning codes are used as in the standard system for flash floods, with the notation that the warning is for

(continued)

Box 9.1 (continued)

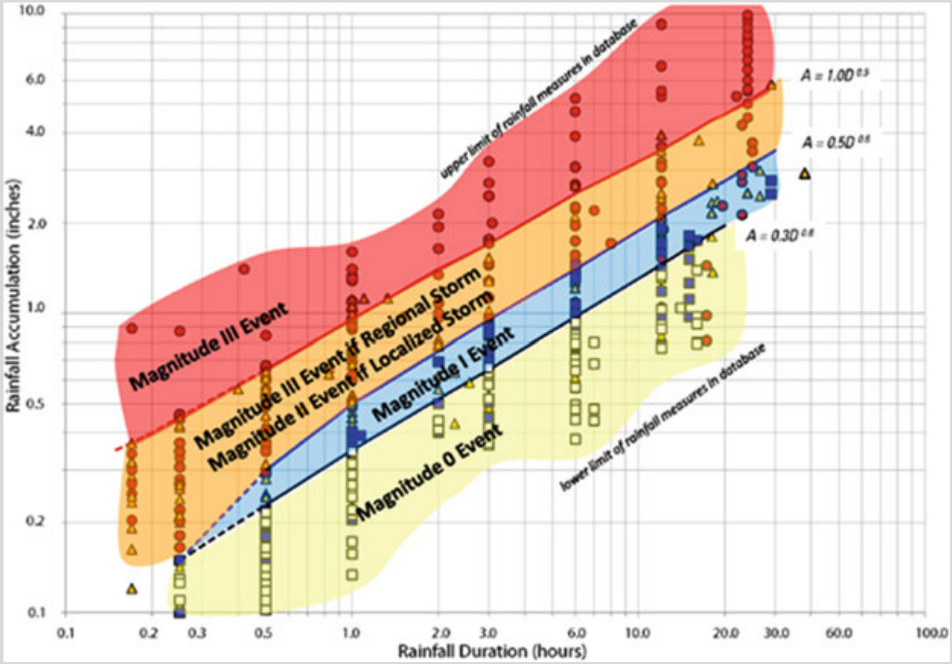

Fig. 9.1 Illustration of threshold rainfall values for recently burned areas in southern California linked to the magnitude of the debris flow impacts. The symbols show observed rainfall values for the historic events used in development of the approach (Courtesy of the U.S. Geological Survey; Cannon et al. 2011)

debris flow. The messages have the following meanings (NOAA-USGS 2005; Restrepo et al. 2008):

- Outlook – issued soon after the fire is contained but before winter storms. Identifies areas that could potentially be impacted by floods or debris flows
- Watch – issued when forecast precipitation approaches threshold values, providing lead times from a few hours to up to 3 days, but while the occurrence, location and/or timing of an event is uncertain
- Warning – issued when an event is imminent, occurring or has a very high probability of occurring, presenting a risk to life or property. Warnings are based on observed or forecast precipitation exceeding threshold values and the lead times provided are ideally up to 1 day ahead but can be as little as 30 min

For example, emergency response actions to a 'Watch' can include mobilisation of staff, positioning of emergency response vehicles in areas at risk, and road closures. In practice, warnings are usually issued if thresholds exceed those for a Magnitude I event (Jorgenson et al. 2011). In the first season of

(continued)

Box 9.1 (continued)

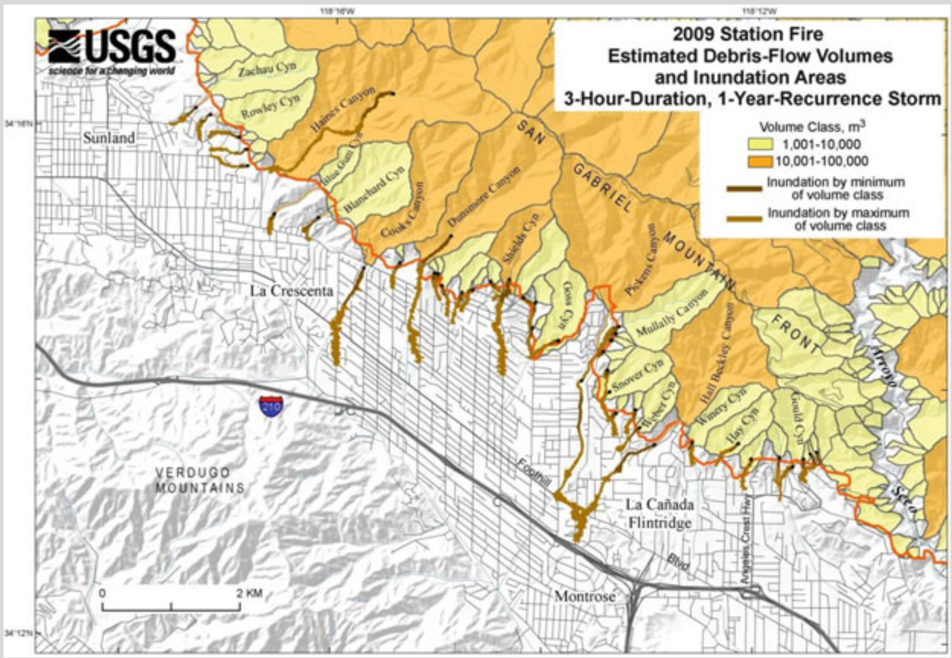

Fig. 9.2 Example from a set of maps generated for the 2009 Station fire in Los Angeles County showing potential debris flow volumes in response to a 1-year-recurrence, 3-h-duration storm, and areas that these volumes of material can impact (Courtesy of the U.S. Geological Survey; Cannon et al. 2009)

operation (2005/2006), 39 warnings were issued of which 11 were for events which generated debris flows. The Probability of Detection score for these events was 92% with a False Alarm Rate of 72%, although there may have been additional debris flows which did not reach the watershed outlet or were stopped by debris retention basins (Restrepo et al. 2008).

To assist with deciding which catchments are potentially at risk, following each major wildfire the USGS produces hazard maps for the areas affected. These include the following two types of outputs (a) probability maps based on a logistic multiple regression approach which takes account of the burned extent, soil properties, basin gradient and storm rainfall and (b) debris flow volume maps (e.g. Fig. 9.2) based on a multiple-regression model that takes account of basin gradient, burn extent and storm rainfall (Cannon et al. 2009, 2010). Relative hazard ranking maps are also produced. This information is made freely available in reports, information sheets and on the USGS website.

Since the start of operations, an intensive research campaign has also been performed each winter, with the real-time observations made available to operational forecasters. The location for these studies is changed each year,

(continued)

Box 9.1 (continued)

Fig. 9.3 Shared Mobile Atmosphere Research and Teaching Radar (SMART-R) C-band radar at the Old El Toro Marine Base during the 2007/2008 observation campaign (NOAA/National Severe Storms Laboratory http://www.nssl.noaa.gov/debrisflow07/DSCN0045.jpg). These instruments have since been provided with dual polarisation capability and renamed as CPOL radars (Jorgenson et al. 2011)

choosing a recently burned area each time. Typically the instruments which are deployed include a C-band weather radar (Fig. 9.3), a wind profiler, a GPS humidity station, a weather station, tipping bucket raingauges, and soil moisture, pore pressure and water level sensors (Restrepo et al. 2008; Jorgenson et al. 2011). For the radar, a 5-min scan cycle is used with 12 elevation angles over the range 0.5–19.5°. A high resolution LiDAR topographic survey is often flown and post storm field surveys are routinely conducted to assess the impacts of any debris flows which occur.

Since the 2008/2009 campaign, the hourly mobile radar outputs have also been fed into the National Weather Service's multi-sensor precipitation product (NMQ). The 2009/2010 campaign was also the first in which the mobile radar had dual polarisation capability, and this provided significant improvements in rainfall measurement accuracy compared to the two closest S-band radars in the national network. This was due both to the mobile radar being sited closer to the burn area (12 km rather than 75 and 88 km) and the improvements arising from the dual polarisation upgrade (Jorgenson et al. 2011).

(continued)

Box 9.1 (continued)

In addition to the operational benefits from the research observations, post-burn areas also provide a good testbed for studying debris flow processes. This is because of the low rainfall thresholds for initiation that result in debris flows occurring more frequently than in unburned areas, providing more opportunities to collect useful information. Current research is focussed on developing improved approaches to defining thresholds, possibly including additional factors other than rainfall, and the use of empirical and physically-based forecasting and hazard mapping models (Restrepo et al. 2008; Cannon et al. 2008).

9.2 Debris Flow Risk Assessments

9.2.1 Definitions

There are many definitions of debris flows and a simplified view might be that they fall part-way between river flash floods (primarily water, but with some sediment and debris) and landslides (primarily soil and rock, but with some water). In practice, debris flows fall within a range which extends from hyperconcentrated flows (sediment-rich streamflow) through to mudflows, debris avalanches, shallow landslides and rockfalls. However, more specific criteria have been proposed and some examples are summarized in Table 9.2. As noted by Iverson (1997) "the diverse nomenclature reflects the diverse origins, compositions, and appearances of debris flows, from quiescently streaming, sand-rich slurries to tumultuous surges of boulders and mud".

Debris flows are usually conceptualized as originating in an upstream source or initiation zone before flowing downhill along a transit zone to dissipate in a debris fan at the lowermost end (e.g. Costa 1984). During heavy rainfall, some processes which typically lead to the initiation of flows include infiltration causing shallow landslides, entrainment of debris by overland flows, and rapid erosion at channel or flow constrictions. Factors such as shallow, unconsolidated superficial deposits, steep slopes and a lack of vegetation also make debris flows more likely, and snowmelt is sometimes a factor.

Regarding flow paths, Hungr et al. (2001) note that "….the key characteristic of a debris flow is the presence of an established channel or regular confined path"…" which is likely to be a first or second order drainage channel or an established gully that controls the direction of flow and in which debris flow is a recurrent process". However, in the early stages, some debris flows primarily flow overland, entraining vegetation, soil and other debris as they move downhill. These are called hillslope, overland or open-slope flows and can consolidate into more damaging channelized flows.

In watercourses, observations and simulations typically show that the flow moves in a series of surges, and that the debris front (or 'head') remains relatively dry and tends to restrain the more fluid flows further upstream (e.g. Iverson 1997). Boulders

Table 9.2 Some examples of definitions or defining characteristics of debris flows (including flows from causes other than rainfall in some cases)

Reference	Definition and/or defining features
Iverson (1997)	Involve gravity driven motion of a finite but possibly changing mass of poorly sorted, water-saturated sediment that deforms irreversibly and maintains a free surface. Flow is unsteady and nonuniform, and is seldom sustained for more than 10^4 s. Peak flow speeds can surpass 10 m s^{-1} and are characteristically so great that bulk inertial forces are important. Total sediment concentrations differ little from those of static, unconsolidated sediment masses and typically exceed 50% by volume. Indeed most debris flows mobilize from static, nearly rigid masses of sediment, laden with water and poised on slopes
Jakob (2010)	A flow of saturated non-plastic mineral and sometime organic debris in a steep channel that includes some 50–70% solid grains by volume, can attain flow velocities in excess of 10 m s^{-1} and can range between 10 and 10^9 m^3 in volume. Mud flows can be contrasted by higher water content and a plasticity index of >5%.
World Meteorological Organisation (2011)	This is a phenomenon in which soil and rock on the hillside or in the riverbed are carried downward quickly under the influence of continuous rain or torrential rain. Although the flow velocity differs by the scale of debris flow, it sometimes reaches *or* exceeds 40 km h^{-1}, thereby destroying homes and farmland in an instant

and other types of debris are also often deposited along the sides of the watercourse to form natural embankments or 'levees', with additional material entrained by channel erosion as the flow progresses. At the lowermost extent, debris fans then form following significant decreases in slope and/or widening of the channel; for example at the foot of a range of hills or mountains. The distance from the initiation zone to the centre of the deposition area is often called the runout distance, although this term sometimes includes the runout length of the debris fan also.

9.2.2 Modelling

Debris flow models are widely used to improve understanding of the risks and causes of flows (e.g. Takahashi 1981; Iverson 1997; Dai et al. 2002; Rickenmann 2005; Rickenmann et al. 2006; Hürlimann et al. 2008). Some key outputs of interest include the runout distance, the extent of the debris fan, and the potential impacts, usually expressed in terms of a typical flow, velocity and/or depth. These parameters reflect both the extent and the damage-causing potential of the flows.

Ideally models should represent both the initiation and transport of flows. For flow transport, the main techniques which are used include:

- Statistical/empirical methods – such as linear and multiple regression; for example relating the runout distance to mean slope and estimates for the total volume of debris, or the deposition area to the volume of debris, or the mean front velocity to slope and depth

- Flow routing models – simplified equations for the flows and velocities based on a mass balance, sometimes using Monte Carlo or random walk models to represent spreading effects in the debris fan
- Hydraulic (numerical) models – one-dimensional (1-D) or two-dimensional (2-D) approximate solutions of the full equations for unsteady flows, which are typically solved using finite difference, element or volume techniques. Both channel characteristics and a digital elevation model are normally required, and airborne Light Detection and Ranging (LiDAR) survey measurements are increasingly used in this type of study (see Chap. 5)

Statistical techniques are necessarily approximate and normally do not provide estimates for the depth or velocity of flows. However, they can be particularly useful for initial or regional hazard assessments. Methods based on easily estimated parameters such as elevation and hill slope are also useful to assist with rapid appraisals following natural disasters (e.g. Coe et al. 2004).

Flow routing techniques have the advantage of a more physically-based approach but require more detailed input data and are formulated in terms of flows, rather than parameters which are often of more interest, such as depths and velocities. Hydraulic modeling techniques help to overcome this limitation, and allow for the influences of changes in slope and channel characteristics along the flow path, which can be significant. However, if a one-dimensional approach is used this still requires a separate empirical or conceptual model if depths and velocities are to be estimated in the debris fan. By contrast, a two-dimensional approach requires fewer assumptions but the data requirements and time and expertise required to calibrate these types of model are greater and suitable calibration information is often lacking.

More generally, even with the most sophisticated approaches, there are still many sources of uncertainty and issues for research and debate. For example, in flow routing and hydraulic models, flows are normally assumed to be single-phase or quasi-homogeneous, with the flow characteristics (or rheology) depending on factors such as the grain size distribution, material types and water content. However, an alternative is to use a two-phase approach, with separate equations for the solid and fluid components.

The details of the interactions between the debris and water components and the terrain and built environment are also difficult to capture, such as scour and entrainment and the influences of deposited materials at bends and structures. Mechanisms for flow initiation are another source of uncertainty and empirical models are typically used, taking account of factors such as local topography such as swales or depressions, geology, soil types, slope, groundwater flows and vegetation cover. However, in some cases, damaging flows result from an accumulation of slope failures at several locations which is a complex situation to represent in a model. Other challenges include estimating the likely total volume of debris during the event and – for unsteady flow models – the magnitude and time evolution of the inflows. Given these uncertainties, sensitivity tests or more formal estimates of uncertainty are generally advisable. However, despite these difficulties, models are a useful tool for estimating the hazard from debris flows and potentially for flow forecasting, as discussed in the following sections.

9.2.3 Hazard and Evacuation Maps

Hazard maps typically present estimates for the likely extent and magnitude of debris flows in a region or community, showing areas at risk, topography, critical infrastructure, and rivers and other natural features. Some applications include assessing the risk for insurance purposes, zoning and emergency planning. To help with interpreting and presenting information, Geographic Information Systems (GIS) are widely used and the resulting maps are increasingly published on websites (e.g. see Box 9.1).

The main techniques which are used in this type of analysis include expert opinion, historical evidence, and modelling. Some potential sources of information on previous flows include anecdotal evidence, dendrochronology and geomorphological studies, post-event surveys, photogrammetry, and aircraft-based and satellite observations. Indeed, following Typhoon Morakot in Taiwan in 2009 (see Table 9.1), one novel approach to obtaining post-disaster evidence of the impacts was to use an unmanned aerial vehicle (UAV) (Tsao et al. 2011). In particular, LiDAR surveys are increasingly used to estimate flow volumes and distributions by comparing surveys before and after events.

More generally, as discussed in Chaps. 6 and 7, having procedures in place for flood data collection and post event survey can assist with future hazard assessments. Some guidelines on survey techniques include:

- Ministry of Construction (1999) – which discusses field survey techniques in Japan for identifying the physical and socioeconomic risks of debris flows
- Hübl et al. 2002 – which considers techniques for European mountain disasters generally, and includes templates and photo-guides for recognizing and capturing key information relating to debris flows

Several organisations also maintain national catalogues or inventories of past debris flow events and associated damages. For example in Switzerland (Hilker et al. 2009) the national database covering floods, debris flows, landslides and rockfalls includes information on:

- Locality
- Date and time
- Type of damage-causing process and secondary processes
- Triggering weather conditions
- Description of the event
- Number of dead, injured and evacuated people and animals
- Affected objects and estimated direct cost of damage
- Further information or details, if available (stream discharge, deposited debris volume, etc.)

Regarding the use of models, given the various uncertainties in outputs, Hürlimann et al. (2008) suggest that empirical and flow routing techniques are more suited for developing 'preliminary' hazard maps whilst numerical models are best used for site-specific ‘final’ hazard maps. This situation is similar to that for river flash flooding, for example, where methods based on flash flood indicators are sometimes used to provide an initial assessment, followed by more detailed hydrodynamic modeling studies for specific locations (see Chap. 8). Some examples of applications of these techniques for debris flows include studies in Venezuela (Lopez and Courtel 2008) and Taiwan (Hsu et al. 2010).

Risk-based techniques are also widely used to assist in prioritizing structural or non-structural interventions. As discussed in Chap. 7, risk is usually estimated from the combination of probability and consequence, where here the consequences are typically expressed in terms of quantities such as the number of properties likely to be affected or the potential economic damages. These estimates can also be included in cost-benefit or multi-criteria analyses, although this is a developing area for debris flows (e.g. Jakob et al. 2011a).

However, given the various uncertainties in the analyses, risk estimates for debris flows are often confined to an indicative assessment such as high, medium or low. For example, hazard matrices are widely used with colour-coded entries according to the probability of the event and the likely depth and intensity at the locations of interest. In some cases, though, there is sufficient historical information to derive frequency-based probabilities, and these are typically based on estimated debris volumes for a number of events. Sometimes it is also possible to estimate the potential damages to property by modelling the influences of factors such as deposition depth or impact pressure.

As for other types of flash flood (see Chap. 7) the vulnerability of individuals and communities should also be considered. For example, for landslides and other sediment-related hazards, Australian Government (2001) notes that “individual/community attitudes to acceptable or tolerable risk may be affected by:

- available resources
- personal or community economic situation
- commitment to property
- individual or community memory and experience with risk
- ability to transfer risk
- government regulations/requirements
- whether the risk analysis is believed
- changing community values and expectations”

Vulnerability studies therefore provide a useful guide to particular groups which may need help during an event. For example, in Japan (MLIT 2007), one estimate suggested that “sixty-three percent of the dead or missing in sediment-related disasters between 2004 and 2006 *were* people requiring assistance during a disaster including the elderly.” As discussed in Chap. 7, on evacuation maps it is therefore often useful to include information such as the locations of shelters and medical facilities and of groups likely to require particular assistance.

9.3 Warning Systems

9.3.1 Monitoring

Warning systems for debris flows often rely on monitoring of rainfall, flows and ground conditions. Some examples include systems in Canada (Jakob et al. 2011b), Japan (Osanai et al. 2010), Taiwan (Wu 2010), Switzerland (Badoux et al. 2009), the USA (Baum and Godt 2010; Box 9.1) and Venezuela (Lopez and Courtel 2008). Wieczorek and Glade (2005) also review a wide range of other approaches internationally.

Typically observations are relayed to local authorities or a regional operations centre using telemetry systems, often supplemented by site observations made manually by staff or volunteer observers. As discussed in Chap. 3, approaches to telemetry include radio, satellite, meteor burst, landline and cellular (GSM or GPRS) techniques, whilst observers typically use cell-phones or hand-held radios. To improve resilience, dual-path telemetry systems are increasingly offered as an option by equipment suppliers; for example combining cellular- and satellite-based approaches.

Telemetry-based systems have the potential to provide frequent updates (e.g. 5-min, hourly) by day and night, but sometimes fail due to instrument problems and other issues, such as rockfalls and vandalism. Also, due to cost, it is often only possible to install instruments at a fraction of the sites of interest. By contrast, manual observations are more subjective and more difficult (and risky) to make at night and during heavy rainfall. However the experience and interpretation of observers provides valuable additional information and staff can be sent to locations where event-specific issues have been reported such as debris blockages at bridges, and to high risk locations where there is no other type of monitoring.

Reports from residents are also potentially useful; for example, some common precursors of a debris flow include rumbling sounds, water levels decreasing although rainfall is continuing, and river water becoming muddy or including driftwood (e.g. MLIT 2007; World Meteorological Organisation 2011). Some warning systems therefore combine the best of both approaches; for example, in Switzerland a real-time web-based decision support system for flash floods and debris flows combines descriptive information from observers with telemetered observations and rainfall and river flow forecasts (Romang et al. 2011). This component is integrated into a wider map-based system which also considers other types of natural hazard (Heil et al. 2010; see Chap. 6).

For automated monitoring of rainfall, the techniques which are used include raingauges, weather radar, satellite precipitation estimates and multi-sensor precipitation estimates. As discussed in Chap. 2, each approach has its own strengths and limitations in terms of accuracy, resolution, reliability and cost. For example, with raingauges, it is sometimes impractical or too expensive to establish a dense network covering the headwaters of all high risk areas. However, if a weather radar network is available, this usually provides a wider spatial coverage, although again with some measurement and sampling issues, again as discussed in Chap. 2. Satellite-based estimates also provide an option, although are usually at a coarser resolution than radar observations and with more uncertainties in the outputs. However, the Tropical Rainfall Measuring Mission (TRMM) research satellite carries a space-borne radar providing direct estimates of precipitation in low- to mid-latitudes and its successor – the Global Precipitation Mission – should provide more accurate estimates with near global coverage.

For ground-based monitoring, many of the river and soil moisture monitoring techniques described in Chap. 3 are potentially of use, although in-stream river level sensors are often avoided due to the risk of damage by debris flows. Instruments in nearby catchments sometimes also provide a useful indication of the debris flow risk in an area. In research studies, a wide array of devices is used, including piezometers, tensiometers, electrical conductivity sensors, hydrophones, and load cells (e.g. Itakura et al. 2005; LaHusen 2005; Reid et al. 2008). However, for operational applications, the techniques which tend to be used include:

- Imaging – CCTV, webcams or video cameras for visual monitoring of the flows, sometimes combined with near real-time image processing
- Geophones – for measuring ground vibrations, particularly from the passage of the initial debris flow front
- Pore pressure sensors – transducers installed in channels and potential flow initiation areas with various forms of protective housings/surrounds
- Soil moisture – dielectric, heat and other types of sensor for measuring soil moisture content at different depths, where this is potentially a factor in flow initiation
- Ultrasonic, laser or radar sensors – downward-looking, non-contact devices mounted on bridges or other structures which detect the distance to the flow surface, and hence provide an estimate for the flow depth (e.g. Fig. 9.4)

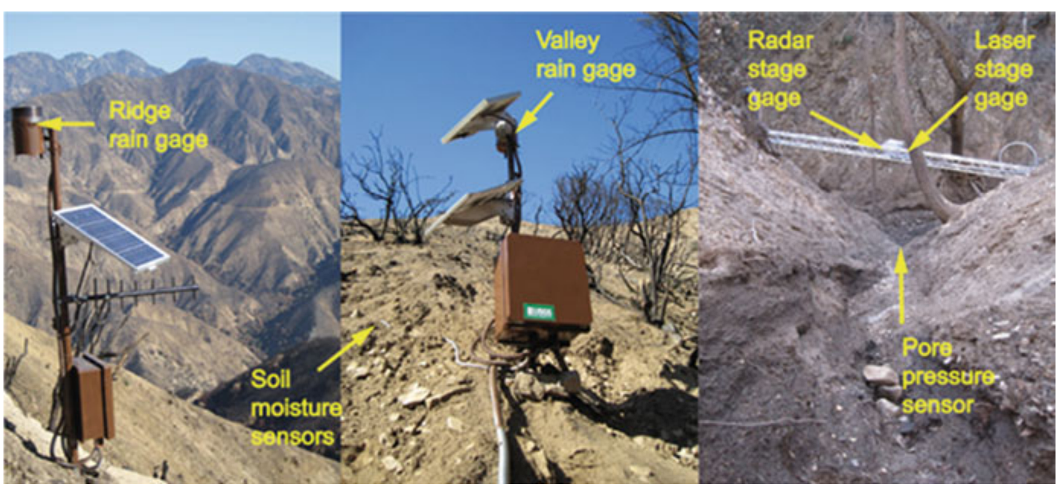

Fig. 9.4 Illustration of instruments installed by the U.S. Geological Survey for monitoring flash floods and debris flows in a small basin in the Arroyo Seco canyon in California, which was one of many canyons affected in the 647 km^2 Station Fire of August and September 2009. Values are reported at 0.1–2 s intervals during rainfall (except for soil moisture readings) and at 1-min intervals otherwise for display on a publicly-accessible website, using radio telemetry to the ridge raingauge location and then a cell-phone modem (courtesy of the U.S. Geological Survey; http://landslide.usgs.gov/monitoring/arroyo_seco/)

- Wire sensors – an array of ‘trip wires’ stretched across a watercourse with a voltage applied producing a signal from each wire as it is cut by the flow. Other methods which work on a similar principle include infrared sensors which rely on interruption of a beam, and suspended weighted wires (‘pendulums’) which move on impact with a debris flow

Estimates for velocities can also be obtained by using pairs or series of sensors installed along the direction of travel, such as geophones or ultrasonic sensors. As discussed in Chap. 12, particle image velocimetry techniques provide another option and are increasingly used for both river and debris flows.

As for rainfall observations, each approach has its own strengths and limitations; for example trip wire sensors need replacing after each event and can be cut by animals or falling trees, and geophone and seismometer outputs can be affected by other sources of vibration such as earth tremors and rock falls (e.g. Arattano and Marchi 2008). If a suitable bridge is not available, ultrasonic, laser and radar sensors require a solid mounting point, unlikely to be affected by any future flows, and some imaging techniques are affected by fog or require lighting to operate at night.

As in other types of early warning system, it is therefore often advisable to use multiple sensors in a range of locations to provide additional backup and resilience, in some cases installing two or more sensors at critical locations. For example, where budgets allow, a typical configuration is to install geophones at several locations along a watercourse, with raingauges and soil moisture probes in the headwaters, and cameras, non-contact sensors, pore pressure sensors, trip wires and/or pendulums at one or more key locations. However, as discussed in Chaps. 2–7, monitoring networks need to be adapted to the situation under consideration, taking into account the level of risk, likely times of travel, the warning lead times ideally required, tolerance to false alarms, and other factors.

Given the uncertainties in the timing and locations of debris flows, mobile observing stations are sometimes used on a seasonal basis (e.g. Box 9.1) or as an event develops, provided that there is sufficient lead time available for deployment. For example, in Taiwan, since 2004 truck-based systems have been available to move to critical locations once a typhoon warning has been issued, and are equipped with a raingauge, geophone and spotlight-equipped controllable CCD cameras, with satellite telemetry to the operation centre (Yin et al. 2007).

9.3.2 Thresholds

As in all flash flood warning systems, a basis is required for deciding when to issue warnings. Again, threshold values are widely used which – once exceeded – lead to a decision being made; for example on activating a response plan, starting more frequent monitoring, or issuing warnings to the public. Some alternative names include triggers, alarms, critical levels and criteria. In real-time operation, thresholds are typically evaluated automatically using the alarm handling options in a telemetry or decision support system.

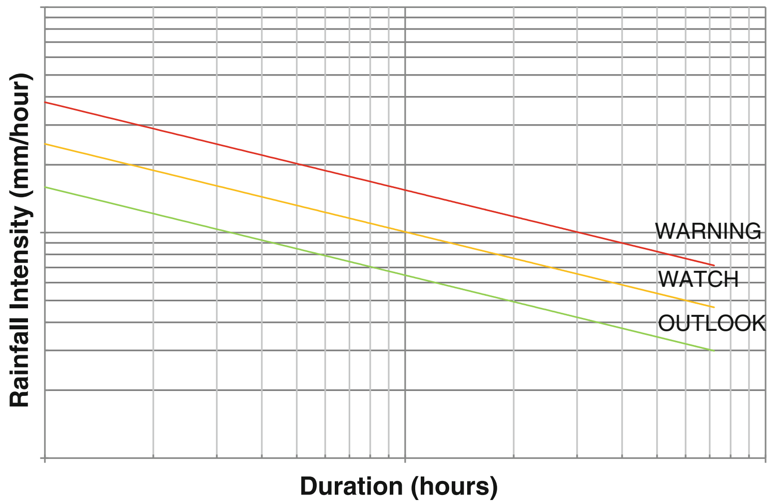

Fig. 9.5 Illustrative example of rainfall depth-duration thresholds for different stages of debris flow warning

Chapters 5, 7 and 8 describe some of the techniques which are used to define thresholds and monitor their performance. However, for debris flow applications, rainfall thresholds are perhaps the most widely used approach. Typically values are defined in terms of the depth or intensity of observed rainfall for a given duration which – past experience shows – is likely to cause debris flows, or at least lead to an increased risk (e.g. Fig. 9.5; see Box 9.1 also). Power-law relationships are widely used (e.g. Caine 1980; Guzzetti et al. 2008; World Meteorological Organisation 2011) and, over time, are then refined based on performance monitoring and the findings from post-event reviews.

However, the resulting values are normally site specific and cannot easily be transferred between regions or countries due to the wide variations in the conditions which trigger debris flows. Additional options include using indicators of the storm type (e.g. Jakob et al. 2006) or – in locations where snowmelt is a factor – the snow water equivalent depth. As discussed in Box 9.1, threshold values may also need to be revised temporarily following wildfires. Also, in locations where antecedent soil moisture conditions are a factor, the cumulative rainfall in the preceding days, weeks or season is sometimes used, or a wetness index (e.g. Wieczorek and Glade 2005; Reid et al. 2008; Baum and Godt 2010).

Forecast values for rainfall are also increasingly used, such as from nowcasts or the outputs from Numerical Weather Prediction (NWP) models. With the latest rainfall forecasting systems (see Chap. 4) forecasts are typically provided at a resolution of 1–4 km and issued at intervals of 1–15 min (nowcasts) and 1–6 h (NWP). For example, in Japan, threshold values (or critical lines) for debris flow warnings are defined nationally on a 5 km grid based on 1-h rainfall accumulations and a soil wetness index computed from a conceptual rainfall-runoff model (Osanai et al. 2010). In operational use, grid-based maps are then produced based on 1–3 h ahead rainfall forecasts. The presentation options available include delineation of areas of heavy rainfall and the direction of motion, and colour-coded maps to indicate the level of risk in each 5 km square, based on a four-stage warning system.

When using rainfall forecasts, since the uncertainty increases with lead time, the maximum lead time to use operationally ideally needs to be assessed through performance monitoring and forecast verification studies of the types described in Chaps. 4, 5 and 7. Also, to account for any systematic or other differences in measurement systems, threshold values should normally be calibrated based on the same approach to be used operationally, such as raingauge or weather radar observations. When rainfall forecasts are used as the primary input, a similar approach would ideally be adopted based on long-term reforecasts or hindcasts of the types described in Chap. 4.

Although rainfall thresholds provide an indication of the potential for debris flows, thresholds based on direct observations of flow initiation and transport are more suitable for providing site-specific warnings; for example, using ultrasonic, radar, geophone, soil moisture and tripwire sensors (e.g. Arattano and Marchi 2008; Badoux et al. 2009). Of course the lead time provided is shorter from this approach. However, in some cases, just a few minutes can be useful; for example for activating electronic signs or barriers at low water crossing points or sirens in residential areas. Multimedia warning dissemination systems can also send email and text messages to large numbers of subscribers in a short time (see Chap. 6).

The thresholds which are used are specific to the type of instrument, and include values for depth, rate of impact, and pressure as well as the one-off signals provided by tripwires and pendulums. For instruments which rely on detecting sound or vibration, additional rules are usually needed to filter out influences from other sources, such as rockfalls. More generally, as discussed in Chap. 7, it is worth noting that the actual response time available following detection of an event is reduced by other factors, such as the time taken to receive data, and the times needed to take decisions and issue warnings to the appropriate people. There is usually also a trade-off between lead times, 'hit rates' and false alarms as discussed further in Chap. 8 in relation to flash flood warnings for rivers. The performance measures used – such as the False Alarm Ratio and Probability of Detection – are also useful for debris flow applications and are discussed in Chaps. 5 and 7.

Another way to provide more accurate warnings – with longer lead times – would be to use a real-time process-based or conceptual forecasting approach. For example, models of this type are widely used for river forecasting applications and often include both data assimilation and probabilistic components (see Chaps. 5 and 8). Typically these are operated within a real-time forecasting system able to gather data, schedule model runs, and post-process model results into map-based, graphical and tabulated outputs.

However, for debris flows, there have been relatively few applications of this type due to the many uncertainties in the analyses, although this is an active area for research. Perhaps the most widely studied application to date has been for the initiation of shallow landslides, which sometimes develop into debris flows. Typically the modelling component consists of a conceptual or physical-conceptual soil moisture accounting model and a slope stability model (e.g. Wieczorek and Glade 2005; Misumi et al. 2005; Schmidt et al. 2008; Segoni et al. 2009). Models of this type are potentially also useful for off-line studies to define threshold values for real-time use; for example accounting for a range of different initial conditions, catchment characteristics and rainfall intensities and durations (e.g. Baum and Godt 2010).

9.4 Summary

- Debris flows are one of the most challenging types of flash flood to predict. However, many successful warning systems have been developed, with notable examples from the USA, Canada, Japan, Taiwan and several European countries. The choice of approach depends on the equipment which is already available for other applications (e.g. weather radar networks), the operational requirement (e.g. for minimum warning lead times), budgets, the level of risk and a range of other factors.
- Due to the complexities of modeling the initiation and transport of debris flows, the risk at a regional level is often assessed using historical evidence and expert judgement. Regression based approaches are also widely used based on relationships between slope, debris volumes and other parameters. By contrast, the use of numerical models tends to be confined to higher risk locations when there is sufficient information available for calibration.
- In debris flow warning systems, the monitoring techniques which are used include raingauges, weather radar and non-contact ultrasonic, laser and radar devices. More specialized techniques have also been developed which rely on the detection of soil moisture, pore pressures, the vibration caused by the flow (e.g. geophones), imaging of surface flows, or the passage of a debris flow front (e.g. trip wires).
- Rainfall depth-duration thresholds are perhaps the most widely approach for deciding to issue warnings. Power law relationships are typically used with numerous examples reported in the literature, although coefficients are normally site specific. Rainfall forecasts are also increasingly used and provide additional lead time although with greater uncertainty when compared to the use of observed values.
- When monitoring flow initiation or transport directly, warning thresholds are also required for these observations; for example based on flow depths or breaking of a trip wire. Often several instruments of each type are installed for additional resilience, sometimes combined with dual-path telemetry. Mobile monitoring stations are also sometimes used when there is sufficient time available for deployment; for example following a typhoon warning. However, debris flow forecasting techniques remain an area for development although shallow landslide models show potential.
- For the future, the development of process-based modelling techniques is one priority area both for refining risk estimates and real-time forecasting of debris flows. Some key factors to consider include the multi-phase nature of flows and flow erosion, entrainment and deposition processes. Research also continues into the mechanisms for the initiation of debris flows and the development of more sophisticated forms of warning thresholds.

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Chapter 10
Urban Flooding

Abstract In urban areas, significant amounts of surface water runoff can occur during heavy rainfall or rapid snowmelt, leading to flash floods if the drainage network has insufficient capacity. When floods occur, the severity depends on a wide range of factors including the topography, urban landscape and pre-existing flows in the surface and sub-surface drainage networks. There are sometimes also interactions with the flows in rivers which pass through the area. Given this complexity, the provision of flash flood warnings is often a challenge and the methods which are used range from rainfall depth-duration thresholds to real-time hydrodynamic models. This chapter provides an introduction to these topics and to the methods used to assess the risk from flash flooding.

Keywords Surface water flooding • Pluvial flooding • Flood risk assessment • Hydrodynamic model • Monitoring • Thresholds • Warning • Forecasting

10.1 Introduction

Flash floods in urban areas arise for many reasons. For example, rivers and smaller watercourses may go out of bank and drainage systems overflow. However another significant cause is surface water runoff which the drainage network is unable to handle. This usually results from heavy rainfall or rapid snowmelt and some typical meteorological causes include thunderstorms, mesoscale convective systems, rising air temperatures, and tropical cyclones, hurricanes and typhoons.

The extent of flooding depends on a complex set of interactions between the surface and sub-surface drainage networks and features in the urban environment, such as road embankments, walls, and buildings (e.g. Figs. 10.1 and 10.2). Additional complications may arise from factors such as sewer flooding, runoff from surrounding hills and influences from control structures such as weirs and flow diversion channels. The impacts also vary widely, with a potential risk to life when levels or velocities are

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Fig. 10.1 Illustration of box culvert with trash screens, outflows at manhole cover (© Crown Copyright 2010, Defra 2010), side weir in canal and weir in river diversion channel

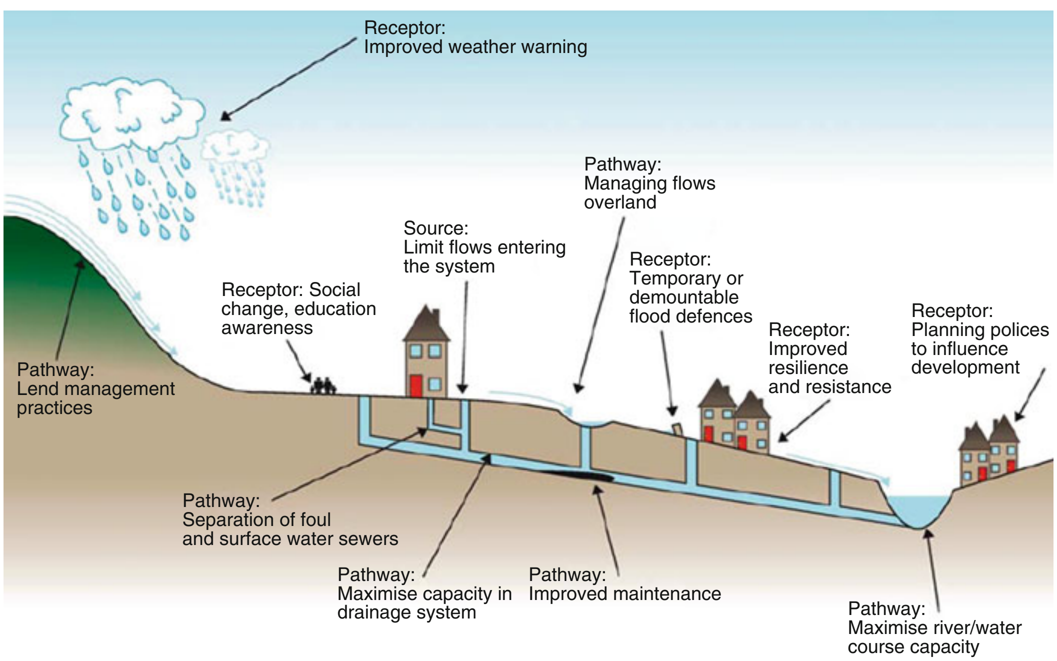

Fig. 10.2 Mitigation measures which can be considered to reduce surface water flood risk (© Crown Copyright 2010, Defra 2010)

high, particularly to people in vehicles and in underground areas such as basements, subways and underpasses. For example, Table 10.1 summarises the causes and impacts for several surface water flooding events. By contrast, in some cases less severe (nuisance) flooding occurs repeatedly at the same locations causing significant health and economic impacts (e.g. APFM 2008).

Providing flood warnings for these types of situations is often a challenge due to the combination of meteorological and other factors. This is a developing area and, as a result, many national flood warning services offer only a limited service for this type of flooding. For example, the dissemination of warnings is sometimes limited to civil protection, local government and other staff with responsibilities during a flood emergency. Indeed, in some cases, this type of flooding is specifically excluded from the warning service, although this position can be difficult to maintain due to public and political pressure for an all-encompassing service.

Table 10.1 Some examples of surface water flooding events

Location	Year	Impacts	Causes
Houston, Texas	2001	In the Houston area, "22 people were killed and more than 45,000 homes and businesses flooded. More than 70,000 vehicles were flooded" (U.S. Department of Commerce 2001). A large-scale evacuation of patients was required from the Texas Medical Centre and underground portions of downtown Houston were flooded	Flash flooding from heavy rainfall and thunderstorms associated with Tropical Storm Allison following its initial landfall in Texas, and a second landfall in Louisiana. For example, in Texas, rainfall exceeded 250 mm in a few hours in the Houston area, reaching 660 mm in 10 h at Great Bayou. Floods resulted from surface water runoff and urban watercourses overflowing
Mumbai, India	2005	Extensive flooding of the city and suburbs resulted in more than 400 fatalities from flash floods and landslides. More than 100,000 residential and commercial establishments were damaged and 30,000 vehicles (Gupta 2007)	Monsoon rainfall with a 24-h total of almost 1000 mm; the flooding was exacerbated by high tides which impeded drainage and resulted in extensive sewerage pollution
Hull, UK	2007	Approximately 8,600 homes and 1,300 businesses were flooded due primarily to the drainage network being overwhelmed	Heavy sustained rainfall on 25 June of about 110 mm followed weeks of wet weather. Over 90% of the city lies below high tide level and so relies heavily on pumped drainage (Coulthard et al. 2007)

Another consideration is that, due to the potential for more than one source of flooding, there is sometimes confusion about the roles and responsibilities for providing flood warnings in urban areas. However, this is typically resolved through the development of joint flood response plans, combined with flood risk modelling studies to better understand the causes of flooding. Community-based flood warning systems also have a valuable role to play and – in some lower risk situations – a simple approach may be sufficient; for example, using storm spotters, police patrols, and other volunteer weather watchers in combination with general flood watches from the national service (e.g. FEMA 2005). Regular public awareness campaigns are also useful in helping to raise awareness amongst residents and vehicle drivers of the potential signs (and risks) of flooding and the most appropriate actions to take.

Despite these difficulties, warning systems are increasingly operated or under development for urban areas. For example, Box 10.1 describes the approach used in the Tokyo Metropolitan Area. Where a service if offered, the meteorological observation and forecasting techniques used are generally the same as those for other types of flash floods and include raingauges, weather radar and nowcasting approaches (see Chaps. 2 and 4). However, some of the flood-related monitoring, warning and forecasting components differ and are described in this chapter.

In addition to flood response planning, some other factors which usually contribute to the effectiveness of a warning system include an appropriate choice of warning dissemination techniques, community engagement activities, emergency response exercises, post-event reviews and performance monitoring. These topics are discussed in Chaps. 6 and 7 and further information is available in guidelines for urban flood risk management such as those produced by APFM (2008), UNESCO (2001) and the World Meteorological Organisation (2011). Chapter 12 also discusses some recent developments in monitoring and forecasting techniques which are potentially of use in urban areas, including phased array weather radars, wireless sensor networks and adaptive sensing techniques.

Box 10.1 Urban Flood Warning, Tokyo Metropolitan Area

Since 2000, the National Research Institute for Earth Science and Disaster Prevention (NIED) in Japan has been developing X-band weather radar systems for flood warning and other applications (Maki et al. 2005; http://www.bosai.go.jp/). This includes the development of advanced approaches for both precipitation and wind field estimation. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) now operates a network of X-band radars across Japan which covers three metropolitan areas and eight cities using 26 radars. These complement the 46 longer-range but lower resolution C-band Doppler radars operated by the Japan Meteorological Agency (Fig. 10.3).

Within the Tokyo Metropolitan area, a research project (X-NET) was established in 2008 to serve as a test bed for urban flood warning, landslide warning,

(continued)

Box 10.1 (continued)

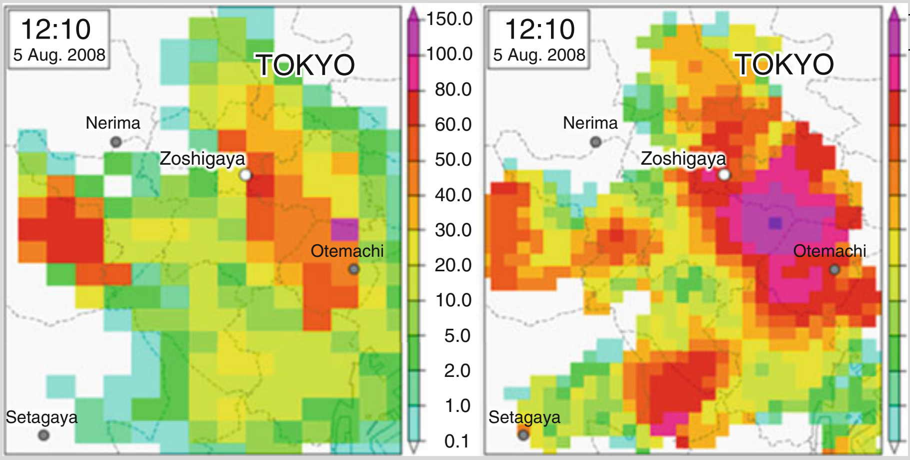

Fig. 10.3 Illustration of the differences in resolution between outputs from the national C-band radar network and X-NET network for a heavy rainfall event in the Tokyo area on 5 August 2008 (NIED)

severe wind warning and other applications. The metropolitan area extends for about 50 km around Tokyo and has a population of more than 34 million people in five cities, including Yokohama city. Rainfall intensities can exceed 100 mm h^{-1} in the most extreme events and flash flooding and landslides are a frequent occurrence.

The organisations which are contributing to the project include NIED and more than ten other governmental, university and research institutes in Japan and Korea. Approaches to precipitation estimation are also being developed in collaboration with the NSF Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) in the USA.

The experimental network includes 11 radars from different agencies and covers an area of about 200×200 km^2; this includes the NIED X-band radar in Kanagawa prefecture which has been operational since 2003 (Fig. 10.4). As for the other two NIED radars, this has a range of about 80 km and has dual polarisation capability. For the research radars in the network, there is also the opportunity to use adaptive scan strategies to focus on the main areas of storm development. Real-time observations are also available from about 150 raingauges in the Tokyo area.

During the initial design and commissioning of the X-band radars, extensive trials were performed using comparisons with the values from raingauge and disdrometer networks. A 2D video disdrometer was also used to provide estimates of droplet sizes along the radar beam path (NIED 2005). In operational use, corrections are applied for ground clutter, attenuation, non-hydrometeors and a range of other factors. Areas of signal extinction are also identified in

(continued)

Box 10.1 (continued)

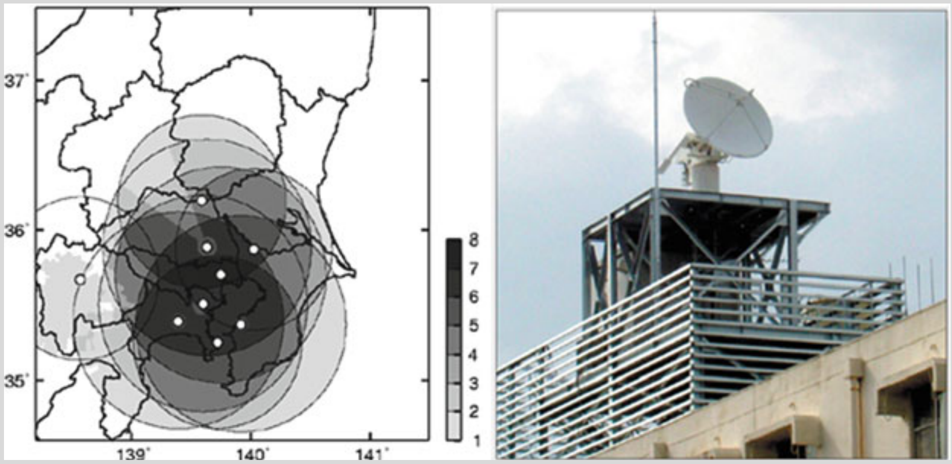

Fig. 10.4 Map of the X-NET observation area at a height of 2 km. The *white circles* show the locations of the radars; two of these are MLIT operational polarimetric radars and the others are research polarimetric and Doppler radars. The photograph shows the X-band radar in Kanagawa prefecture for which the dish diameter is about 2 m (Maki et al. 2010; NIED 2005)

the composite outputs. For medium to heavy rainfall, estimators based on the specific differential phase have been found to overcome many of the issues with attenuation and drop size influences often encountered with X-band radars (NIED 2005; Maki et al. 2010).

Outputs from the X-band network are provided at a 500 m resolution and 5 min intervals and include rainfall, wind speed and wind direction, information on hydrometeor type, drop-size distributions, catchment rainfall and wind gust data. The areas covered by each instrument are overlapping, also allowing detailed investigation of the three dimensional structure of storms in near real-time. The outputs are also used as inputs to nowcasting algorithms and for the data assimilation schemes in cloud-resolving atmospheric forecasting models.

For flood warnings, end users of the experimental products include Fujisawa City of Kanagawa Prefecture, the Edogawa ward of Tokyo, the Tokyo Fire Department, private railway companies and a construction company (Maki et al. 2010). Yokohama City are also evaluating the use of rainfall estimates within an existing automated warning system which uses flashing lights and voice alerts to warn users of river parks in the city of approaching high water levels (Chandrasekar and Maki 2011).

Real-time urban flood prediction and landslide disaster prediction support systems are also under development. For example, the flood model uses distributed rainfall-runoff and hydraulic drainage components to estimate flows along major drainage paths and flood depths, velocities and damages.

(continued)

Box 10.1 (continued)

Outputs are provided at 10 min intervals at a spatial resolution of 10 m (Nakane and Matsuura 2007; Maki et al. 2008).

A network of water level sensors has also been established along key roads to assist with the verification of estimated water levels. The model outputs are available via a website and mobile phone to local government offices, volunteer groups and non-profit organisations. Some of the applications which are being evaluated include assisting with traffic regulation and providing warnings for flooding in subterranean spaces such as subways, underground malls, and private basements. For example, during a heavy rainfall event in July 2010 in the Tama region of Tokyo, with a rainfall intensity of 50–70 mm h^{-1}, the Tokyo Fire Department was able to take the decision to start flood protection measures using temporary levees 30–50 min earlier than would have been possible based on the standard heavy rainfall and flood warning system (Chandrasekar and Maki 2011).

10.2 Flood Risk Assessments

10.2.1 Definitions

In urban areas, stormwater is usually collected by a network of surface drains and culverts and sub-surface pipes (e.g. Fig. 10.5). In older systems the sub-surface components are often combined with the wastewater side of the system but modern systems generally use separate paths.

If the capacity of the system is exceeded temporarily then water typically flows along paths, roads and other features to collect in low lying areas, with rapidly rising water levels in some cases. This type of flooding is often called pluvial flooding and can be broadly defined as (Falconer et al. 2009) "…flooding that results from rainfall-generated overland flow and ponding before the runoff enters any watercourse, drainage system or sewer, or cannot enter it because the network is full to capacity". Some typical causes include (Dale et al. 2012):

- drainage capacities being insufficient
- rainfall intensities being too high to be able to enter the gully points that connect to underground drains
- local problems such as culvert blockage, meaning road and other drains cannot convey the flows they are supposed to
- rainfall flooding in areas where no suitable drains exist

Many complications can also occur. For example, if a river passes through an urban area, high river levels sometimes impede drainage at river outfalls or river flows enter the drainage network. When rivers and streams are routed through

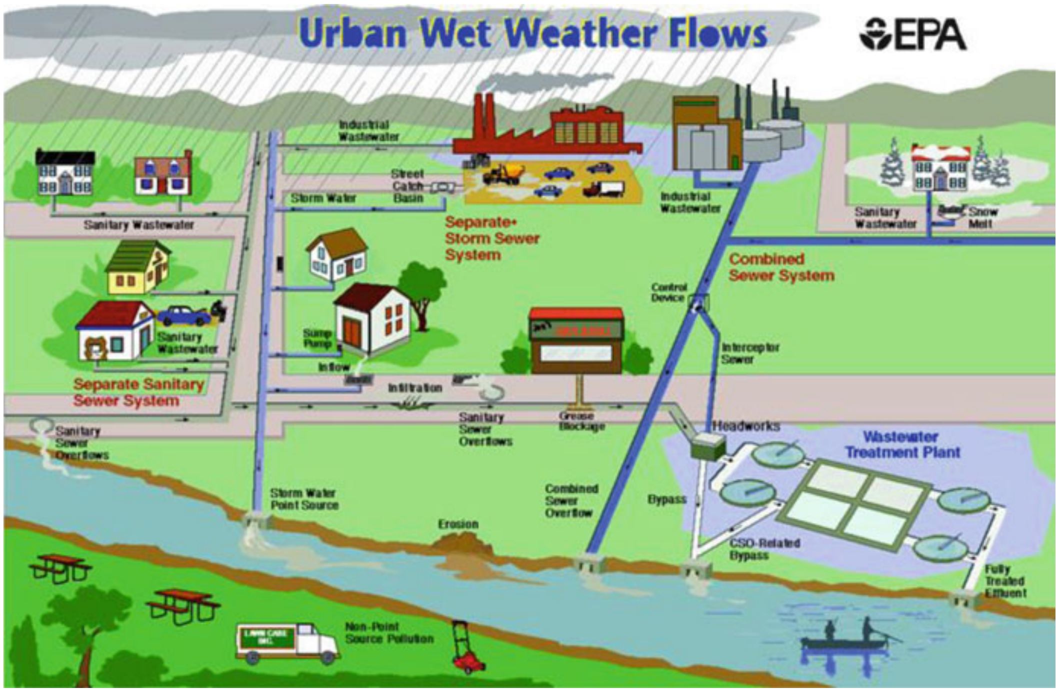

Fig. 10.5 An illustration of the three types of systems that are used for sewage and stormwater disposal (US Environmental Protection Agency http://www.epa.gov/)

underground culverts and tunnels, this potentially adds to the flood risk if blockages occur from debris or garbage or the flow capacity is exceeded. The risk of this occurring is particularly high at grills or trash screens designed to stop debris entering the system. Other possibilities are that water will flow back from the sewer system into streets and properties, or that some areas will be affected directly by river flooding (see Chap. 8).

Where combined river and surface water flooding occurs, the relative magnitudes and timing of flows also need to be considered. For example, the runoff in urban watercourses often arises primarily from local rainfall, and some catchments may lie entirely within the urban area. In contrast, high flows in rivers typically occur over longer timescales and are sometimes related to more distant storms which may have little impact locally. In addition, in urban areas, the percentage of rainfall appearing as runoff is usually much higher than for a natural catchment due to the impermeable nature of roads, car parks and other features. However, local measures to reduce runoff are increasingly incorporated into new housing developments, such as Sustainable Drainage Systems (SUDS) or Low Impact Developments (LIDs).

10.2.2 Modelling

To assess the risk from surface water flooding, the two main components which need to be considered are the capacity of the drainage network and the magnitude and timing of the surface water runoff. Usually the complexity of the approach is tailored to the perceived risk, based on factors such as the number of properties which could potentially be affected and the damages caused in previous flood events (if any). Some particular aspects which may need to be modeled include (Schmitt et al. 2004):

- the transition from free surface flow to pressure flow in the sewer pipes
- the rise of water level above ground level with water escaping from the sewer system
- the occurrence of surface flow during surface flooding, and
- the interaction between surface flow and pressurized sewer flow

For the sub-surface component, hydraulic modelling packages are widely used for design and operational studies. Typically these represent the flows in the main pipes in the system and any valves, pumps, service reservoirs, storage tanks, overflow weirs and other components which significantly affect flows and pressures. Although setting up and calibrating models of this type can be a considerable undertaking, reasonable results are often obtained; for example when comparing flows and pressures at key locations in the network with values obtained from observations.

However, estimating surface water flows is normally more of a challenge since usually it is not possible to represent the runoff generated by every road, garden, car park, industrial area and other features. For example, sometimes even small changes in topography such as roadside kerbs can significantly alter the flow characteristics, with larger features such as road and rail embankments acting as barriers to flow. The amount of runoff generated is also typically affected by antecedent conditions in areas of open land such as parks, gardens and wasteland, and there may be flood detention areas and flow control structures to consider.

Rather than attempting to model all of these influences directly, in design studies simple empirical techniques are widely used in which indicative values are estimated for wider areas (e.g. World Meteorological Organisation 2009); for example, assuming typical land-cover characteristics for separate subcatchment areas and using unit hydrograph or conceptual rainfall-runoff relationships. Idealised design storms – expressed in terms of a depth, duration and storm profile – are typically used, based on a rainfall-frequency analysis. For example, urban drainage networks are typically designed to handle rainfall events up to a given return period or annual exceedance probability, such as a 1 in 30 year design event.

A simple approach to estimating flood extents is then to assume that some proportion of the rainfall volume is distributed over the terrain. The simplest approach of all is to assume that all rainfall appears as surface runoff, and this might be regarded as a worst case in which the drainage system is completely overwhelmed or blocked. Alternatively, estimates are derived based on assumptions about the percentage of rainfall removed by the drainage network and absorbed by infiltration and other processes. Flows are then typically routed between subcatchment areas using steady state, kinematic wave or other approaches, taking account of the conveyance network, stormwater detention areas and other features.

However, the development of more sophisticated approaches is an active area for research, with an increasing number of practical applications. Typically analyses are performed using digital terrain models in a Geographic Information System (GIS) environment to identify flow paths from the mosaic of land features. A grid-based

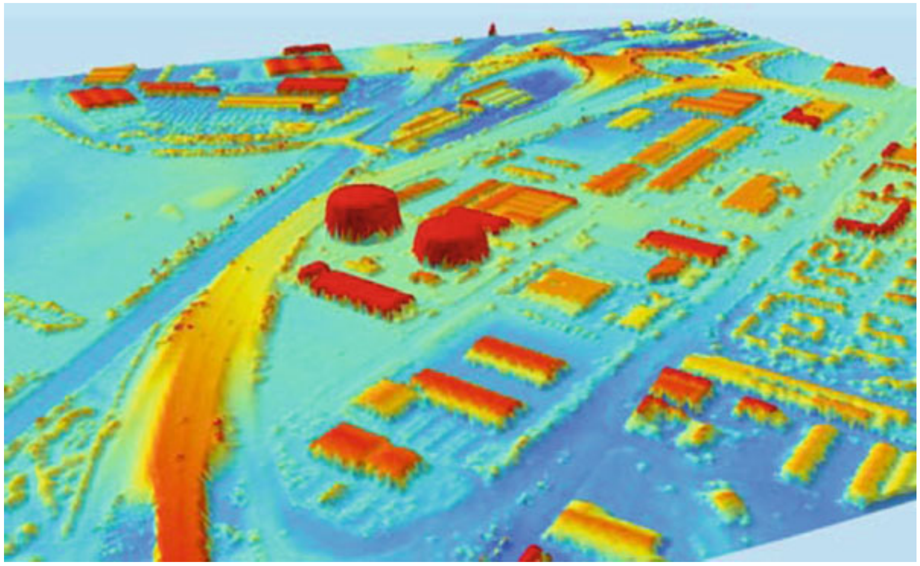

Fig. 10.6 A 3D view of an urban area based on LiDAR remote sensing observations (© Crown Copyright 2010, Defra 2010)

approach is then used for the surface water component, with an allowance for the infiltration characteristics and antecedent conditions at each grid cell. In recent years this approach has been facilitated by developments in remote surveying techniques; for example airborne LiDAR (Light Detection and Ranging) surveys (e.g. Fig. 10.6) typically now achieve vertical and horizontal accuracies of the order 0.1 m vertically and 1m horizontally or less from aircraft or helicopters (see Chap. 5). Automated approaches to flow-path generation and catchment delineation have also been developed, taking account of the dimensions and topology of all key 'as-built' and land use features within an urban area (e.g. Maksimović et al. 2009).

For the hydraulic modelling component, one possibility is to use a de-coupled approach in which the surface and sub-surface elements are modeled separately and the interactions are represented in an approximate way; for example by assuming a depth or volumetric factor at each interconnected grid cell to take account of the (estimated) fraction of runoff flowing into the sub-surface network. Alternatively, a fully coupled approach is increasingly used to reduce the number of assumptions required about how these components interact. In some cases river levels and flows need to be considered where these potentially have an influence on the flood extent.

For the surface water component, typically a one- or two-dimensional hydraulic modelling approach is used (e.g. Fig. 10.7) based on the St Venant shallow water flow equations (e.g. Leopardi et al. 2002; Hunter et al. 2008; Pender and Néelz 2011). As discussed in Chap. 5, a 1-D approach is generally computationally faster but usually requires some manual definition of flow paths and is less suited to modelling open areas. In contrast, 2-D models overcome some of these difficulties but are usually slower to run, although faster rapid flood spreading and other techniques are becoming commercially available. Also, this type of model can potentially include some of the details of the interactions between flows and

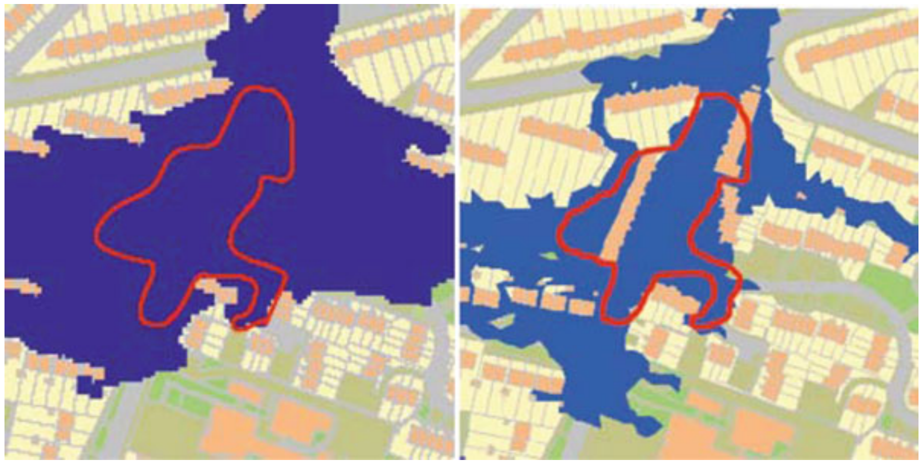

Fig. 10.7 Comparison of how different modelling approaches can produce very different results. Each image maps a flooding event with an annual 1-in-30 chance of occurring. The *red line* indicates the actual extent of flooding at that level. The methods used were 2D overland routing of a uniform rainfall event (*left*) and a decoupled sewer model and 2D overland routing (Cabinet Office 2008, Contains public sector information licensed under the Open Government Licence v1.0.)

embankments, large buildings and other structures. In some cases, a three-dimensional (3-D) modelling approach is potentially useful for detailed investigations of specific flooding issues, such as in evacuation studies for underground spaces (e.g. Takayama et al. 2007)

Whichever approach is chosen, there is generally a need to refine the initial estimates based on discussions with local flood experts and site visits to review potential flow paths. There are also possible advantages in using a mixed approach, with simpler 1-D models in areas where only approximate estimates are required and 2-D models in higher risk locations (e.g. Saul et al. 2011). Compared to flood modelling for rivers (see Chap. 8), in urban areas the uncertainties are generally higher; however useful results can be obtained and are widely used in investment planning and developing flood response plans. As discussed in Chap. 7, flood warning or evacuation maps are also widely used to assist operational staff during flood events and some particular features of interest for surface water flooding include:

- Low points on roads such as underpasses where there is a significant flood risk
- Culverts and other locations where there is a risk of debris blockages
- Equipment depots where key maintenance equipment is stored
- Flood detention areas and other structures essential to urban flood management
- The locations of key telemetry and camera monitoring sites
- Locations where potentially dangerous depths or velocities are suggested by model outputs

Chapter 7 also discusses a range of other items which could be included such as the locations of medical facilities, vulnerable groups, and critical infrastructure.

10.3 Warning Systems

10.3.1 Monitoring

In urban areas, many of the same monitoring techniques are used as for other types of flash flooding, and discussed in Chaps. 2 and 3. These include raingauges and river level gauges. The extent to which events are monitored in real-time depends on a number of factors including the level of flood risk, previous flooding problems, and budgets (e.g. UNESCO 2007). However the following techniques are widely used, with the choice of approach depending on the main types of flooding issues to be considered:

- Blockage risks – differential pressure sensors, water level sensors, and time lapse or video cameras or webcams at trash screens, grills and other blockage-prone locations
- Heavy rainfall – tipping bucket, impact, hot plate or weighing raingauges providing rainfall measurements at point locations typically every 1–15 min. Also, X-, C- or S-band weather radar observations may be available as part of a national network (see Chap. 2)
- Sub-surface drainage network – pressure transducer, ultrasonic and other gauges for measuring pressures, flows and other parameters in pipes, pumps and other components
- Watercourse levels – pressure transducer, float-in-stilling-well, bubbler, ultrasonic or radar gauges installed in or above open drains and culverts and minor watercourses and reporting at intervals as frequently as every minute, depending on the application

Typically cellular, landline, radio or satellite telemetry is used (see Chap. 3), in some cases with automated transmission of alerts to operational staff by email, text message and other approaches (see Chap. 6). Outputs are usually made available either via a stand-alone telemetry system or integrated into SCADA or other existing systems.

Some typical requirements for instruments installed in urban areas include ease of maintenance, low cost (e.g. to allow a dense network to be installed), low visual impact (both from amenity and vandalism considerations) and the facility to report at frequent intervals either continuously or when key threshold values are passed. The resilience to debris is another factor for instruments installed in culverts and watercourses.

For rainfall observations, another consideration is the spatial resolution which is achievable since spatial variations often have a strong influence on the locations and extent of flooding. There have been several studies on the spatial and temporal resolutions ideally required for monitoring rainfall in urban areas (e.g. Berne et al. 2004; Einfalt et al. 2004). However, results tend to depend on the watershed area(s), application, climatic regime and analysis techniques used. In general though, the requirements are often considerably more demanding than for river catchment monitoring;

for example, Schilling (1991) suggests indicative values of a raingauge density of at least one gauge per square kilometer and a temporal resolution less than or equal to 5 min.

As indicated earlier, the main options for monitoring rainfall are weather radar and raingauges and, where the flood risk is high, it may be worth installing a dense raingauge network. For example, in Harris County in Texas, a network of more than 100 combined river and raingauge sites is operated in an area of approximately 4.500 km^2 in and around the city of Houston http://www.harriscountyfws.org/. Solid state impact sensors are also proving useful for monitoring rainfall in urban areas and are small enough to be installed at a wide range of locations (e.g. Basara et al. 2009; Koskinen et al. 2011).

Often, though, there are budgetary or other limitations on the number of gauges used, so weather radar observations provide another option for more detailed spatial observations. Typically, for the national networks operated by meteorological services, the spatial resolution is in the range 1–5 km for C-band and S-band devices (see Chap. 3). However, as discussed in Box 10.1, shorter range gap-filling X-band radars are increasingly used in high risk locations, and typically provide outputs at a grid scale of 1 km or less at time intervals of about 1 min or more. Some examples for urban areas include applications and research projects in the USA (McLaughlin et al. 2009), Japan (see Box 10.1) and Europe (http://www.raingain.eu/; Pedersen et al. 2010).

As discussed in Chap. 12, several other precipitation measurement techniques are under development. These include adaptive sensing techniques which use X-band or phased array radars and have the potential to track and visualize storms as they cross urban areas. In particular, due to their small size and weight, X-band phased array radars are potentially well-suited to installation on buildings and other urban structures. Multi-sensor precipitation products provide another option and are available operationally in some countries (see Chap. 2), whilst microwave attenuation techniques, using existing cell phone links, are another possibility for the future.

10.3.2 Thresholds

In flash flood warning systems, thresholds are widely used to provide operational staff with alerts when observations or forecasts exceed pre-defined values. The actions to take are typically defined in written flood warning procedures and flood response plans, as discussed in Chaps. 6 and 7.

When a surface water or pluvial warning service is offered, perhaps the most widely used approach is to use rainfall depth-duration thresholds based on raingauge or weather radar observations and/or rainfall forecasts. These define the depths of rainfall in a given period (or range of periods) which are likely to result in flooding issues. To provide some allowance for the spare capacity in the drainage network, different thresholds are sometimes defined depending on whether the rainfall occurs during dry weather or following a period of wet weather. This general approach is also widely used in river and debris flow warning systems and is discussed in more detail in Chaps. 8 and 9, together with some examples of the types of verification techniques which are used.

For urban areas, threshold values are typically defined based on an examination of rainfall accumulations during previous flooding events, in some cases supported by modeling of the drainage network. Alerts are then issued to locations which are potentially at risk based on flood risk maps and/or records of previous incidents. However, due to the complexities of the flood response, often it is only possible to give a general indication of the risk, such as that provided by the "Urban and Small Stream Flood Advisory" http://www.weather.gov/glossary/ type of alert used in the USA which:

> ….alerts the public to flooding which is generally only an inconvenience (not life-threatening) to those living in the affected area. Issued when heavy rain will cause flooding of streets and low-lying places in urban areas. Also used if small rural or urban streams are expected to reach or exceed bankfull. Some damage to homes or roads could occur.

When rainfall forecasts are used (see Chap. 4), alerts are increasingly issued in probabilistic terms. For example, in England and Wales, an Extreme Rainfall Alert service is available to local response organisations to "…forecast and warn for extreme rainfall that could lead to surface water flooding, particularly in urban areas" (Met Office/Environment Agency 2012). Alerts are issued at county level "…..when there is a 20% or greater probability of the following thresholds being exceeded: 30 mm per hour, 40 mm in three hours or 50 mm in six hours". The potential benefits of the service include:

- Impacts on road network, local transport and associated services minimised
- Local authorities and utility companies better informed to manage their response to surface water flooding
- Staff and resources deployed and managed more effectively
- Equipment, such as sandbags, mobilised and deployed in advance
- Communication teams better informed and prepared to handle media and public response

Research is also underway to develop threshold values adapted to individual locations and regions (Hurford et al. 2011).

In many cases, a key use of rainfall thresholds is to prompt precautionary actions such as placing staff on standby, performing emergency clearances of blocked drains, trash screens and culverts, closing roads and car parks, and alerting the emergency services and other key groups. Where appropriate, additional threshold values are defined for water levels in small watercourses and for differential pressure sensors at trash screens. This then provides a more precise indication of specific flooding issues, albeit at shorter lead times than is possible with rainfall-based values. For example, in some cities in the USA, thresholds based on kerb-side pressure transducers and float switches or downward-looking radar or ultrasonic devices are used to trigger activation of automatic barriers, flashing lights and/or electronic warning signs at flood-prone locations on roads, such as underpasses and low-water crossings (see Chap. 12).

Table 10.2 Some examples of possible ways to improve the warning process and reduce flood risk in urban areas

Item	Description
Access	Alerting people to the dangers of flooding in areas such as underpasses, underground malls and waterside parks using warning signs, flashing lights or barriers
Cameras	Use of cameras with day and night capability for monitoring of known flood-prone locations, using either continuous recording or at set intervals, with images visible over a telemetry system, a secure website and/or sent to operational staff as email attachments
Community engagement	As with other types of flash flood, involving community members in developing flood response plans so that people know the most effective actions to take on receiving a warning, where possible including volunteers as part of the response team (e.g. as flood wardens)
On-site monitoring	Deploying operational staff or trained volunteers to known problem areas for visual monitoring of the situation, with the authority and training to issue warnings directly to the emergency services and other organisations, and possibly directly to residents at risk
Operations centres	Establishing a round-the-clock (24/7) warning service once heavy rainfall is forecast, possibly making use of existing facilities which already operate on that basis (e.g. the emergency services or transport, water supply, traffic management or security organisations)
Telemetry	Using more frequent reporting intervals than is normally used for river monitoring; for example, in some urban flood warning systems, a 1-min interval is used for level gauges in minor rivers and watercourses
Warning dissemination	Use of rapid notification techniques such as sirens, cell-broadcasting, multi-media systems and other approaches (see Chap. 6)

More generally, as for other types of flash floods, the warning lead time provided can potentially be extended by making improvements throughout the monitoring, decision-making and warning dissemination chain. This topic is discussed further in Chaps. 1, 6 and 7 and Table 10.2 illustrates some approaches which are sometimes used for urban areas.

10.3.3 Flood Forecasting

Flood forecasting models provide another way to help staff to decide whether to issue warnings and to improve the warning lead times which are possible. However, for surface water flooding the use of real-time hydraulic models is a developing area and there are few operational implementations internationally.

Typically models are operated in real-time using weather radar or raingauge observations and rainfall forecasts as inputs. For real-time use, one added complexity is that the performance of the drainage system sometimes depends not just on the distribution of rainfall but also on the direction of travel of a storm, again requiring high resolution rainfall inputs to represent this effect.

Another consideration is that in small urban catchments forecast model runs typically need to be performed every few minutes or less to resolve the rise in levels and flows. As for river forecasting models (see Chaps. 5 and 8), the flood inundation extent could potentially be estimated in real-time; for example from a 2-D model or by interpolation from a faster running 1-D model. Alternatively predefined inundation maps could be provided to operational staff as paper copies or via a web-based viewer, with different maps corresponding to different flow or level threshold values.

Some examples of research and pre-operational studies using these approaches include systems in Japan (see Box 10.1), Austria (Achleitner et al. 2008) and the UK (Liguori et al. 2012). Improvements in computing power and algorithms also mean that 2-D modelling is increasingly becoming a realistic proposition for real-time forecasting (Fortune 2009). Other approaches have also been explored, such as fast running data-driven models, and data assimilation using error prediction approaches (e.g. Bruen and Yang 2006).

As in many other aspects of flash flood forecasting, a probabilistic approach is increasingly advocated to assess the uncertainty in outputs. For example, Schellart et al. (2011) discuss a range of pluvial flood modeling case studies in the UK which considered the use of probabilistic nowcasts, statistical downscaling techniques and artificial neural networks. In principle, the probabilistic content of the forecasts should then help with better decision-making in the run up to and during a flood event; a topic which is explored further in Chap. 12.

Some of this development work has also been prompted by the increasing use of real-time control systems in urban drainage networks, in which remotely activated valves, sluice gates and other components are operated so as to distribute water to areas in the system which currently have spare capacity (e.g. Schilling 1989; Schütze et al. 2004). More than 20 cities in the USA, Canada, Europe and Japan now operate these types of system (EPA 2006). Some typical objectives are to reduce operating costs and the number of pollution and flooding incidents; in particular from the outflows into watercourses at Combined Sewer Overflows (or CSOs). Typically operating rules are based on a combination of experience and off-line hydraulic modelling and – due to their complexity – often need to be coded into a decision support system.

10.4 Summary

- Surface water flooding has the potential to affect large numbers of properties and road users, and to present a risk to life. The main cause is usually heavy rainfall although other factors sometimes play a role, such as rapid snowmelt. In some cases the response is complicated by interactions with river flows, and reverse flows back out of drainage and sewer systems.
- In urban areas, surface flow paths are often complex and affected by small-scale features such as roadside kerbs and individual buildings, walls and embankments. Runoff generation processes are also more complex than for rural catchments,

typically comprising a fine-scale mosaic of parks, gardens, open land and more impermeable areas such as roads and car parks. The interactions with the sub-surface drainage network usually also need to be considered.

- Despite these difficulties, in recent years there have been considerable advances in hydrological and hydrodynamic modelling techniques for surface water flooding. For example, several coupled surface and sub-surface modelling packages are now available commercially, using a grid-based representation of runoff processes. Automated procedures are also increasingly used for initial assessments of likely flow paths. Taken together these techniques have greatly facilitated assessments of the flood risk in urban areas, both from surface water alone and in combination with other sources, such as river flooding.
- Due to the complexities of the response to rainfall, many flood warning organisations only offer a limited warning service for surface water flooding. Typically this is based on raingauge or weather radar observations combined with rainfall depth-duration thresholds. Rainfall forecasts are also increasingly used. However, the spatial and temporal resolutions required are usually higher in urban areas than for a river catchment which is a key challenge in providing operationally useful warnings. The use of X-band weather radars is therefore an active area for research, with several operational and pre-operational implementations worldwide. Phased array, microwave attenuation and adaptive sensing techniques also show potential for the future.
- Level, pressure, imaging and flow monitoring devices are increasingly used as part of the warning process, both in the sub-surface drainage network and in urban watercourses and at flood-prone locations on roads and in public spaces. In addition to the techniques used for rivers (see Chaps. 3 and 8), other examples include differential pressure transducers, time-lapse cameras and pressure transducers for pipe flows. A particular focus is often on the risk of blockages and local flooding at obstacles such as trash screens and culverts.
- The use of flood forecasting models is a developing area which in the past was held back due to the requirements for rapid model run times and the complexity of the models required to represent urban flow processes. However, recent advances in computer processing speeds and model algorithms are making the use of real-time hydrodynamic models more feasible, with several pre-operational examples already implemented. In part these developments have been driven by the requirements for real-time control of urban drainage systems.

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Chapter 11
Dams and Levees

Abstract Flash floods usually arise from heavy rainfall resulting in high river levels and – in some cases – debris or surface water flows. However structural and geotechnical issues sometimes play a role and examples include the flash floods due to dam breaks, flood defence (levee) breaches, and glacial lake outburst floods. This chapter describes some of the approaches used to define areas at risk and provide early warnings for these types of event. This includes a discussion of the decision criteria (thresholds) which are typically used in warning systems and the techniques used for monitoring the condition of dams, levees and moraine barriers. Several examples of operational warning systems are also provided.

Keywords Dam break • Levee breach • Flood risk assessment • Flood defence breach • Glacial lake outburst flood • Monitoring • Warning • Forecasting

11.1 Introduction

Whilst most flash floods and debris flows arise from heavy rainfall or rapid snowmelt, there can be a number of other causes or contributing factors. In particular, geotechnical or structural factors often increase the risk of dam breaks or glacial lake outburst floods. On a smaller scale, failures at river flood defences (levees) may lead to rapid flooding of areas that were previously protected from inundation. However, with sufficient warning lead time, residents can move to safer locations and there is sometimes the opportunity to reduce the extent of flooding; for example by drawing down reservoir levels to reduce the risk of dam failure, or reinforcing levees with sandbags and geotextiles.

This chapter discusses some of the monitoring and warning issues associated with these types of flash floods. Although there are many aspects in common, there are some significant differences and these need to be accounted in the design and operation of a warning system. For example, dam breaks and outburst floods often result in deep, fast moving flows which affect areas for many kilometres downstream. Peak

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flows, velocities and depths typically far exceed the values observed even in major river flood events and in some cases flows are funneled down valleys and canyons adding to the destruction. Levees by contrast tend to be constructed in lower-lying areas and, if a failure occurs, velocities reduce as the flow spreads out over the floodplain. However, water depths can increase rapidly and reach dangerous levels particularly where flows are contained by topographic or other barriers. For example, during Hurricane Katrina in 2005, in parts of New Orleans (ASCE 2007) "multiple levee failures inundated some neighborhoods from several sides with such speed that houses filled to their rooftops in minutes". Table 11.1 provides some further background on this event and on several dam and outburst floods.

Table 11.1 Some examples of dam break, outburst flood and flood defence breach events

Location	Year	Impacts	Cause
Johnstown, USA	1889	Some 2,209 people perished and 27,000 people were left homeless in the town of Johnstown due to a dam failure (Frank 1988; McGough 2002). Estimates suggest that the initial peak flow at the dam was about 12,000 $m^3 s^{-1}$ and that the flood wave covered the 22 km to the town in about 1 h (Ward 2011)	An unusually heavy storm crossed the region and continued into the following day, with the 24-h rainfall for the previous day estimated at 150–250 mm (Frank 1988). This resulted in high reservoir inflows leading to overtopping and failure of a poorly-maintained earth embankment dam (see Box 11.1)
Huaraz, Peru	1941	An outburst flood occurred at Lake Palca affecting approximately one-third of the city of Huaraz some 22–23 km downstream. There were more than 6,000 fatalities (Lliboutry et al. 1977).	The flood was caused by overtopping of the moraine dam containing Lake Palca as a result of an icefall into the lake. This caused a second outburst flood at a lake further downstream
Vaiont Dam, Italy	1963	Overtopping of a concrete arch dam resulted in about 2,000 fatalities in villages further downstream (Graham 2000). The flood wave was estimated to reach a peak height of more than 100 m above the dam wall and to reach depths of up to 70 m further downstream	The overtopping resulted from a major landslide into the recently constructed reservoir which was still being filled. The dam structure remained almost undamaged (Bosa and Petti 2011)
Malpasset Dam, France	1959	A flood wave more than 40 m high resulted in approximately 400 fatalities (Delatte 2009). There had been no prior warning of structural issues and the reservoir levels – although high – were not at danger levels	The dam wall cracked and failed due to shifting of the left wall abutment due to a weak seam in the rock. Following several weeks of heavy rainfall, the dam was nearly full for the first time since being commissioned in 1952

(continued)

Table 11.1 (continued)

Location	Year	Impacts	Cause
Henan Province, China	1975	Failure of the Banqiao and Shimantan dams and approximately 60 smaller dams in Henan Province with approximately 85,000 fatalities and 11 million people affected (Si 1998)	More than 1,000 mm of rainfall in 3 days linked to a typhoon caused reservoirs to fill to capacity and in some cases to fail
New Orleans, USA	2005	More than 1,000 people were killed and thousands of homes destroyed. More than 80% of the city was flooded, reaching depths above 10 ft in some neighborhoods (ASCE 2007)	A significant proportion of the flood damages resulted from the failure of concrete floodwalls or overtopping and erosion of levees in more than 50 locations. Pump stations were mainly inoperable

Box 11.1 Johnstown Flood, USA

In 1889, the town of Johnstown in Pennsylvania suffered one of the most damaging floods on record in the USA. This was caused by failure of the South Fork Dam on the East Conemaugh river some 22 km further upstream and 140 m higher than the town. At the time of the disaster, Johnstown was a rapidly growing town with a population of about 30,000 and a major centre for the coal mining and iron and steel industries.

The first survey work for the dam began in 1834 and construction started in 1840 but was suspended in 1842 due to a lack of funds. Work resumed in 1851 and the dam was commissioned in 1853, forming a reservoir known as Lake Conemaugh or the Western Reservoir. Its main function was to provide water to the Pennsylvania Main Line canal and it was operated until about 1863, when it was abandoned due to the increasing competition from railroad operators.

The reservoir was about 3 km long with a capacity of about 16 million cubic metres. The earth and clay dam structure was approximately 284 m long and 22 m high, with a mainly earth core but a slate, shale and rock layer on the downstream side, with rock rip-rap on the downstream face. Outflows were via five 0.6 m diameter pipes under the base of the dam, controlled by valves operated from a wooden control tower. There was also a 25 m-wide spillway for flood flows. A review following the flood by the American Society of Civil Engineers concluded that the dam itself was well designed and constructed (e.g. Frank 1988).

(continued)

Box 11.1 (continued)

In the 1860s and 1870s the condition of the dam gradually deteriorated due to a lack of maintenance and vegetation growth on the dam wall. The pipes and valves were also removed and the control tower destroyed in a fire. The culvert under the dam also collapsed in a flood in 1862 causing further lowering and washing away of the crest. However in 1879, a group of wealthy industrialists purchased shares in the newly formed South Fork Fishing and Hunting Club which was established to develop the reservoir for recreational purposes.

Some early tasks were to repair the damage from the 1862 flood and to lower the dam crest by about 0.6 m to provide a wider roadway for wagons and carriages. However, the repairs were not supervised by a dam engineer and were carried out in an ad-hoc way using earth and clay on top of a layer of hay and straw. The culvert entrance was also blocked and metal screens were built at the top of the spillway to prevent game fish escaping, which acted as a trap for debris and reduced the spillway flow capacity.

From 1881, the lake was then used for fishing, boating and as a summer resort and retreat. In the winter and spring months before the event, there was heavy snowfall followed by heavier than usual rainfall in April and May 1889 (McGough 2002). On May 30th, an unusually heavy storm crossed the region and continued into the following day, causing flooding in many locations in the region, with the 24-h rainfall estimated at 150–250 mm (Frank 1988). This resulted in the highest recorded floods to date in Johnstown itself with some streets flooded to a depth of 2–3 m on the day of the dam failure. The level in Lake Conemaugh also started to rise rapidly and by 11:30 on May 31st had started to overtop the dam wall. By that time, a work crew had already been working for 2 h trying to raise the level of the dam crest, clear debris from the spillway and dig an emergency spillway at the opposite end of the dam.

At 11:00 the resident engineer rode on horseback approximately 4 km downstream to the town of South Forks to warn residents of the risk, and a warning was telegraphed from there to Johnstown, further downstream. This was one of at least three warnings received; however, due to the number of false alarms in the past, these were afforded little attention, and were not widely distributed (McGough 2002). By 13:00 the dam face was beginning to erode severely and emergency works were abandoned at 14:30. At a time placed variously as 14:50 or 15:10, the centre section of the dam gave way (Fig. 11.1). The initial flow was estimated at about 12,000 $m^3 s^{-1}$ and the lake emptied in just 45–65 min (Ward 2011).

As the waters sped down the valley, the debris load increased, adding to the destructive power. One of the witnesses to its passage, John Hess, a railroad engineer, was widely credited with saving many lives in the town of East

(continued)

Box 11.1 (continued)

Fig. 11.1 Artists impression of the South Fork Dam as it appeared when newly constructed and during the breach of 1889, and flood markers on the City Hall in Johnstown showing the peak levels reached in 1889 (21 ft), 1936 (17 ft) and 1977 (8.5 ft) (Art by L. Kenneth Townsend, http://www.shadedrelief.com/, Patterson 2005)

Conemaugh through issuing a warning via a train whistle, and described the approaching flood as "…like a hurricane through a wooded country. It was a roar and a crash and a smash…." (McGough 2002). The flood wave reached Johnstown at 16:07, having travelled the distance from the dam at an average speed of about 5–7 $m\,s^{-1}$.

The wall of water was estimated to be 7 m or more high in places with a sound resembling thunder or an approaching train. Although many survived by swimming or grabbing debris or moving to higher ground or the upper floors of buildings, some 2,209 people perished and 27,000 people were left homeless (McGough 2002). Following the disaster, the dam was not rebuilt and is now the site of a national memorial. However, severe river flooding occurred again in 1936 and a major flood protection project was subsequently completed, which was the second largest in the USA at that time. Despite this, serious flooding occurred again in 1977, resulting in 85 fatalities, leading to a further upgrade of the flood defence scheme, which was completed in 1997.

Providing flood warnings for these types of situations can be challenging due to the combination of meteorological and other factors. However, in high risk situations the decision is sometimes taken to install an early warning system due to the risk to life; for example, until known problems with a structure are resolved, or while engineering works are being performed resulting in a temporary increase in the risk of failure. In some countries, permanent warning systems are also installed at key sites.

In all cases, one challenge is to identify the conditions which might lead to overtopping or collapse of a structure. For example, some typical scenarios for activating a flood response plan include:

- A rainfall or flood forecast indicating that reservoir inflows or river flows could lead to overtopping of a dam wall or levee
- Observations or reports from operators, the public or others that structural problems are occurring or accelerating

As for other types of flash floods, warning systems typically include monitoring, forecasting and warning dissemination components, and the main techniques which are used are discussed in Chaps. 2–7. Chapter 8 also discusses river flood forecasting techniques including the influence of reservoir operations on flood flows further downstream. By contrast, in this chapter the focus is on aspects which are specific to dam and levee failures and to related types of flooding such as glacial lake outburst floods. This includes an introduction to the methods used to assess flood risk and vulnerability and develop emergency response plans, and to structural and geotechnical monitoring techniques.

11.2 Flood Risk Assessments

11.2.1 Definitions

Dam breaks and flood defence (levee) failures both arise from overtopping or damage at water-retaining structures so the flooding mechanisms have many aspects in common.

Some typical contributing factors include high reservoir or river levels, but structural or geotechnical issues alone sometimes result in failures. For example, potential issues include foundation or abutment defects, settlement, liquefaction and root damage from uncontrolled vegetation growth. Physical damage may also occur due to collisions from debris, ice or boats, or corrosion at gates, valves and other structures. Some typical failure initiation mechanisms include erosion, slope instability and piping or seepage through or under the structure.

For dams, the two main types are in-stream or in-line reservoirs and off-line storage reservoirs, such as retarding basins or washlands. In-line dams typically consist of a concrete, masonry, rockfill or earth embankment placed across a river to form a reservoir. Flash floods can then arise at locations further downstream from overtopping, collapse and/or rapid erosion of the dam wall, or from emergency releases to avoid overtopping of the crest. Some dams also have self-priming siphons installed to protect the structure which, once activated, may result in extreme discharges further downstream. As discussed in Chap. 8, most dams have spillways for flood flows and these potentially add to the flood risk at locations downstream.

There have been many studies of the causes and frequencies of failure of dams but results typically depend on the number of countries surveyed, the definitions used, and the level of reporting of incidents. However, for large embankment dams, surveys typically suggest an approximately equal split between overtopping and structural issues, with complete or partial failure rates of the order of 1% of dams constructed (e.g. Foster et al. 2000). For example, a mid-1990s analysis of data for the failure of dams located outside China (ICOLD 1995, in Graham 2000), for dams mainly 15 m or more in height, suggested that:

- The percentage of failures of large dams has been declining over the past four decades; 2.2% of dams built before 1950 failed; less than 0.5% of dams built since 1951 failed
- In absolute terms, most failures involve small dams, which do however make up the greatest proportion of dams in service. The ratio between failed dams of height H to the number of dams built of height H varies little with height
- Most failures involve newly built dams. The greatest proportion (70%) of failures occur in the first 10 years, and more especially in the first year after commissioning
- With concrete dams, foundation problems are the most common cause of failure, with internal erosion and insufficient shear strength of the foundation each accounting for 21%
- With earth and rockfill dams, the most common cause of failure is overtopping (31% as primary cause), followed by internal erosion in the body of the dam (15% as primary cause) or in the foundation (12% as primary cause)
- With masonry dams, the most common cause is overtopping, followed by internal erosion in the foundation
- Where the appurtenant works were the focus of the failure, the most common cause was inadequate spillway capacity

It is however worth noting that figures such as these generally include older structures not built to current standards and that only a small proportion of these cases have led to significant harm to people or property.

By contrast, for off-line reservoirs, failure of the surrounding embankments typically results in flooding more akin to that of a flood defence breach. This then leads to rapidly rising water levels although often without high velocities or significant debris content, except close to the point of failure. Flooding of this type can also occur at polders, where a polder is an embankment which is built to surround and protect an area at risk from flooding. Factors such as wave action, impacts and damage from uncontrolled vegetation growth and burrowing animals sometimes affect the performance of levees and earth embankment dams.

In some cases lakes also present a flash flood risk, particularly when water accumulates behind a temporary natural barrier (Costa and Schuster 1988). Examples include the dams caused by landslides or debris flows into a river, or melt water collecting behind glacial moraine or ice. If the natural 'dam' is overtopped or fails then the resulting flood is often called an outburst flood. Perhaps the most well-known type is a Glacial Lake Outburst Flood (GLOF) which occurs when a moraine or glacial 'dam' fails. The risk is sometimes increased due to the meltwaters resulting from geothermal or volcanic activity, causing outburst floods which – in Iceland – are known as Jökulhlaups (e.g. Snorrason et al. 2000).

More generally, temporary river blockages due to debris flows and landslides often feature in post-event reviews for flash floods, typically causing a build-up of water which is then suddenly released when the blockage clears. As illustrated by the Vaiont Dam and Huaraz disasters noted in Table 10.1, landslides or icefalls into a reservoir or lake also have the potential to cause overtopping of a dam or moraine wall.

11.2.2 Modelling

For dams and levees, as in many other areas of flood risk management, one of the first steps towards prioritizing monitoring and maintenance effort is usually to obtain a better understanding of the risk. The resulting hazard maps and risk rankings are then often used to provide guidance on priorities for establishing early warning systems and developing emergency response plans.

Many countries – such as the USA and UK – have flood hazard mapping programmes in place both for dams and, in some cases, for assessing the risk of flood defence failures. Analyses are typically performed at a national, regional or organizational level for all significant structures, with more detailed assessments for sites with a particularly high risk. This type of assessment can be a major task; for example there are more than 80,000 dams in the USA of which approximately 70% are owned by the private sector (e.g. ASDSO 2012).

Typically the level of detail used in the analyses is related to the risk, with a simpler approach sometimes justified for small dams with just a few properties downstream compared to a large dam upstream of an urban area. For example, the information used in the prioritisation of planning for dam emergencies can include (Australian Government 2009) the following factors:

- condition of the dam and the degree, if any, of dam safety deficiency
- population at risk and community vulnerability
- scale of flood risk costs
- range of other consequences (e.g. on property, the environment, or community value of the dam)
- stakeholder perceptions and expectations
- state of knowledge and planning commitments for different scenarios

This information is typically obtained from sources such as site inspections, reports from dam operators, flood risk maps, community meetings, and discussions with civil protection and emergency response staff. Satellite data and GIS-based analyses are increasingly used to assist with an initial assessment of locations at risk, particularly for glacier dams (e.g. Huggel et al. 2004) and small unregulated dams (e.g. farm dams).

To develop flood risk maps the following two key questions need to be answered: what is the likely scale, mode and time evolution of any breach or failure, and where will the water go once that occurs? The first question is the more problematic, requiring an understanding of the current condition of the structure, potential failure mechanisms, the hydraulic loading, and other factors (e.g. Wahl et al. 2008; de Wrachien and Mambretti 2009; Wahl 2010). Overtopping risks also need to be considered.

For dam failures, one approach is to assume an instantaneous partial or complete failure with the reservoir filled to the crest level; the outflow is then estimated using a simple weir equation assuming a rectangular or trapezoidal opening. Time-varying scenarios for the size and shape of the breach are sometimes assumed. Empirical relationships are also widely used to estimate the peak flow and time to peak of the outflow hydrograph, typically using regressions based on the stored volume, dam height or other factors. However, often the lack of data from past events results in considerable uncertainty in the resulting estimates. In some cases, separate estimates are derived both for clear weather failures and flood conditions where, in the latter case, reservoir inflows and spillway flows also need to be considered.

Some progress has also been made towards developing physically-based models which combine the structural, geotechnical and hydraulic aspects of the problem (e.g. Morris et al. 2008). For example, as part of research studies, fully dynamic models are widely used which represent the time-varying interactions between hydraulic and erosive effects, taking into account typical structural failure modes. However, these remain primarily research tools, although erosion models are increasingly used as a guide to the likely key characteristics of a breach, such as the ultimate width and time for formation (e.g. Wahl 2010).

Probabilistic techniques are also increasingly used both for dams and flood defences, typically using Monte Carlo techniques to explore different combinations of hydraulic loading, asset condition and assumed breach location and dimensions (e.g. Sayers et al. 2002; Gouldby et al. 2008; Huber et al. 2009). For example, for levees these approaches typically consider the embankment system as a whole to better understand the consequences of failure at any one location.

For the second question, of predicting the resulting flow of water, for dam breaks one- or two-dimensional hydraulic models are widely used of the types described in Chap. 5 for river modelling, based on the inflow hydrograph(s) derived from the breach analysis. Similar techniques are used for outburst floods (for example, see Box 10.2). Satellite-based altimetry or LiDAR surveys are again widely used to define the topography along the flow path. However, one key challenge is to parameterise the loss terms in the model to represent factors which are not normally encountered. For example flows may extend up hillsides and pass over bridges and low-lying buildings and contain sufficient mud and debris to affect the flow characteristics. Several dam-break modelling packages are available commercially which provide guidance on the techniques and parameter values to use.

For flood defence breaches, many of the same issues arise although two-dimensional models are more widely used due to the widespread extent of flows compared to typical depths and the need to model flow depths, velocities and paths on the floodplain. In this case, it is often useful to produce maps showing the potential areas of inundation both with and without the scheme in place to illustrate the worst case scenario of complete failure or bypassing of a levee system.

11.2.3 Flood Response Planning

Once the probability of flooding has been estimated, this is typically combined with information on critical infrastructure, residential properties and businesses to develop risk and vulnerability maps. Where only a qualitative estimate is available for the probability of failure, hazard ranking and similar approaches provide a simpler less precise alternative.

The resulting estimates can then be used to guide the development of emergency action plans and longer term measures to reduce flood risk, such as raising or repairing dam walls or levees and prohibiting further building development in areas with a high risk. For example, for dams, plans are typically produced by dam operators and at community, civil protection and regulatory authority level.

As discussed in Chap. 7, flood warning and evacuation maps are widely used both for emergency planning and operational use, and to raise public awareness of the actions to take. Generally, maps need to be clear, easy to interpret and contain all of the key information required by emergency responders. For dams, in some cases it is also useful to indicate areas which – although not directly at risk of flooding – are likely to be cut off, together with bridges which – although unlikely to be overtopped – should be closed due to the potential for clogging by debris (e.g. Australian Government 2009).

When a flood risk starts to develop, some examples of the measures which can be taken include emergency pumping or flow releases at dams, and reinforcement of weak areas or raising defence levels at levees. Other possible actions include precautionary evacuations of areas at risk downstream of the structure and temporary closure of roads and railways crossing the floodplain. As for other types of flash floods, as part of the emergency planning process, analyses are often performed of the time constraints in the warning process. For example, for the case of a sudden unexpected failure at a dam, the time delays in issuing a warning can include (e.g. FERC 2011):

- Detection time – the time taken for the operator's staff to become aware of the problem
- Verification time – the time taken to verify the problem visually or by other means

- Notification time – the time taken to notify the emergency management agency (EMA)
- EMA response time – the time taken to warn and/or evacuate critical residences close to the dam

The sum of these delays can then be compared with the estimated time to impact of the first locations at risk (e.g. residences, campgrounds, roads, critical infrastructure) to see if it is possible to issue a warning in time under current procedures.

If required, some possible ways to streamline procedures include installing additional telemetered monitoring equipment, training local emergency response staff in on-site inspection techniques, and developing pre-defined warning message templates (see Chap. 7). Another option is to adopt faster approaches to issuing warnings, such as sirens and multimedia warning dissemination systems (see Chap. 6). In some cases standard operating procedures are modified to allow dam operators to issue warnings directly to people at risk close to the dam site to reduce time delays further. Tabletop and full-scale exercises are also widely used to help to obtain a better understanding of the delays and bottlenecks in decision making and to test and validate response plans. Providing additional backup contacts and resilience for all components also helps to guard against system failure, or the risk that key people are not available to issue warnings when an event occurs.

As part of the emergency planning process for dams, potential loss of life studies are also often performed for different failure or overtopping scenarios; for example using probabilistic and event-tree techniques. Indeed, the results from these types of study are often a key input when prioritizing dam inspection and upgrade programmes. For a full description, this typically requires consideration of a range of flooding, human response and transportation issues, such as the following factors (Needham 2010):

- The dam-failure flood event, including the dam breach location, geometry and rate of breach development, the reservoir pool level, the time of day, detection time of the dam-failure event relative to failure initiation, and the extent, velocity, depth and arrival times throughout the downstream inundation area.
- The number and location of people exposed to the dam-failure flood event, including the initial spatial distribution of people throughout the downstream inundation area, the effectiveness of warnings, the response of people to warnings, the opportunity for and effectiveness of evacuation, and the degree of shelter provided by the setting where people are located (structure, vehicle, on foot, etc.) at the time of arrival of the dam-failure flood wave.
- The loss of life amongst the threatened population who remain in the inundation area at the time of arrival of the dam-failure flood wave. Loss of life estimates at a specific location take into consideration the physical character of the flood event and the degree of shelter provided by the setting where people are located at the time of arrival and after the flood wave has passed for those who survive it.

In particular, the time of day or night is a key consideration with the speed of response depending on whether people are at work or at home or awake or asleep. However, as for other types of flash flood (see Chap. 1), the minimum warning times required vary widely between locations and organisations. For example, based on data for several dam break events, one review study suggested that the lives of more than 99% of the people at risk could be saved with more than 90 min of warning (Brown and Graham 1988). These types of studies therefore provide a useful input to response planning; however due to the uncertainties involved, more traditional methods such as site inspections and the use of engineering judgment are still essential.

11.3 Warning Systems

11.3.1 Monitoring

When structural issues occur, usually the first action, after notification of the appropriate authorities, is to start more frequent monitoring of conditions. Additional flood risk mapping exercises are sometimes also performed to better assess the risk; for example, in the USA, National Weather Service forecasters have access to a range of GIS-based dam failure and hydraulic modelling tools to model possible scenarios as an event develops (Reed and Halgren 2011).

In many cases, visual monitoring is performed by dam operators and other experts, in some cases supplemented by ad-hoc approaches such as diving surveys. Increasingly, tools such as GPS-enabled laptop or smartphone applications are available to help in inspections and completing checklists. Simulation software using computer game technologies is sometimes also used to train staff in assessing the risks of structural failure (Hounjet et al. 2009).

Automated equipment is also used for higher risk locations, either as part of a permanent warning system, or in response to a developing emergency. The types of equipment used include:

- Embankments and dam walls – instrumentation to record movement, deformation and – for earth embankments – soil moisture and pore pressures, including accelerometers, crack monitors, extensometers, inclinometers, piezometers, pressure cells, pressure transducers, pendulums, seismometers, strain gauges, tensiometers, thermistors, tiltmeters and time domain reflectometry equipment (e.g. Fig. 11.2)
- Survey and remote sensing – ground-based observations by camera, video and thermal imaging, and survey of crest levels and other areas using continuous GPS, marker lights and laser or ultrasonic ranging
- River and reservoir levels – monitoring using float-in-stilling-well, pressure transducer, bubbler, ultrasonic or radar gauges (see Chap. 3), float switches, and sump, drain and borehole level monitoring. For example, for a reservoir, some typical locations for installing level gauges are close to the dam wall and in the area immediately downstream of the dam

Fig. 11.2 Examples of piezometers, an automated in-place inclinometer and a siren used as part of the Tuttle Creek Dam Failure Warning System (Empson and Hummert 2004)

As discussed in Chap. 3, some options for telemetry of observations include landline, cellular, radio, meteor burst, and satellite-based systems, in some cases using a dual-path approach to increase the resilience to telemetry failure. For water level gauges, a particular consideration is whether the recording range is sufficient for potential dam break or levee overtopping conditions and whether electrical equipment for data logging, power supplies and telemetry would remain above those levels. Typically the risk is assessed from flood modelling studies and the equipment is then raised, modified or relocated as required.

In some cases, satellite- and aircraft-based monitoring and photogrammetry techniques are used, particularly for remote reservoirs in mountain regions, such as glacier-dams. There may also be a need to monitor ground conditions upstream of a dam; for example if there is a potential risk of a landslide or icefall into the reservoir. Some of the warning and forecasting techniques discussed in Chap. 9 for debris flows are therefore potentially useful in this situation. For moraine dams, some other factors which need to be considered include the stability of the ice core or permafrost, as discussed further in Box 11.2.

Although there are exceptions, the use of telemetry-based structural and geotechnical monitoring techniques has to date been confined mainly to dams and glacial lakes. However, there is growing interest in using these approaches for levee systems; for example, to obtain a better understanding of overall system performance or for monitoring at high risk locations to provide early warning of potential problems. Since in some cases levee systems extend over many kilometres, one difficulty in the past has been to know where to place instruments; however, fibre optic sensors show potential for low-cost monitoring of movement (strain) and flows (temperature changes) over large distances (e.g. Lougheed 2006).

Box 11.2 Glacial Lake Outburst Floods, Himalaya

The Himalaya extend for more than 3,500 km from Afghanistan in the west to Myanmar in the east and China in the north to Bangladesh in the south. Floods, landslides and debris flows are commonplace and Glacial Lake Outburst Floods (GLOFs) present a particular risk. Typically these form where glaciers recede allowing water to accumulate behind the terminal moraine, which forms a natural dam (e.g. Fig. 11.3).

Some mechanisms for failure or overtopping of the moraine can include rising water levels, seepage, melting of the ice core and surge waves caused by avalanches and landslides into the lake. Landslide dam outburst floods resulting from landslides into rivers can also cause similar problems and the high earthquake activity in the region adds to the risk.

Due to the large volumes of water released, floods can affect areas many kilometres downstream and cross international borders. In some events, it is estimated that peak flows of 30,000 $m^3 s^{-1}$ have occurred with the impacts extending more than 200 km downstream (Richardson and Reynolds 2000). For example, in August 1985, an outburst flood from the Dig Tsho lake in Sagarmatha (Mt Everest) National Park destroyed a hydropower facility which was nearing completion, 14 bridges, 30 houses, and extensive areas of agricultural land (Vuichard and Zimmermann 1987). An estimated three million m^3 of debris were moved over a distance of up to 40 km. Before the event the lake was estimated to have a surface area of 0.6 km^2 with a maximum moraine height of 60 m (Bajracharya et al. 2007).

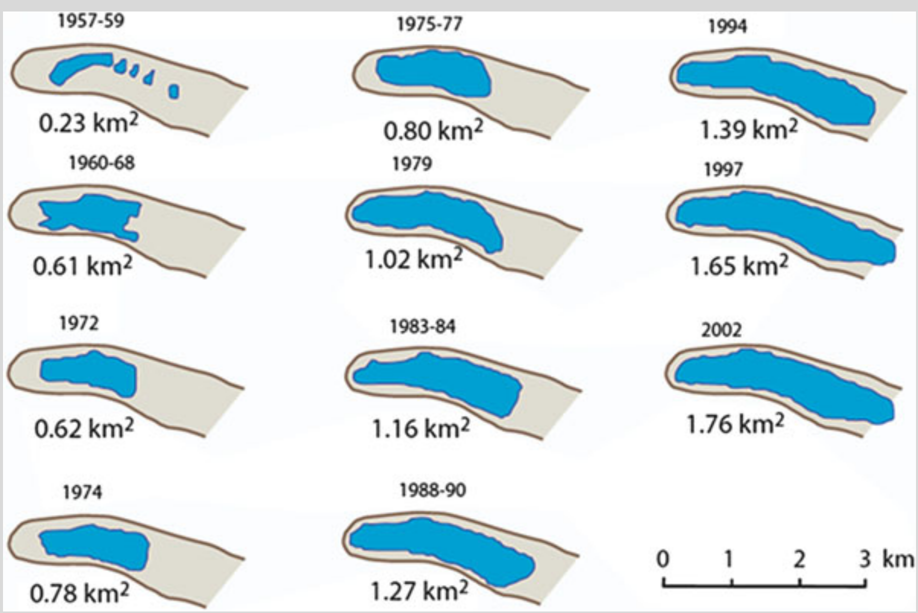

Fig. 11.3 Development of Tsho Rolpa lake; the largest glacial lake in Nepal (ICIMOD; Shrestha 2008)

(continued)

Box 11.2 (continued)

Recent studies suggest that there are more than 8,000 glacial lakes in the Himalaya of which approximately 200 present a significant risk (Ives et al. 2010). The risk assessment was based on a number of factors, including findings from recent site visits, lake size, the rate of rise of water levels, evidence for previous events, and the topographic and geomorphological characteristics within and around the lake and associated glacier. For example, a review of previous studies suggested evidence for more than 34 significant GLOF events in Nepal, the Tibetan Autonomous Region, China and Bhutan alone. The factors assessed on site typically included the dam crest area, height and slope, the moraine seepage and drainage characteristics, and the stability of the ice core and/or permafrost within the moraine. The potential impacts downstream were also considered, taking account of the number of settlements, agricultural land and transport and other infrastructure likely to be affected (e.g. Shrestha et al. 2010; ICIMOD 2011).

Given the remoteness of much of the region, remote sensing plays an important role in this type of study, supplemented by topographic maps and aerial photographs where possible. Dam breach and hydrodynamic modelling studies have also been performed for some high risk locations and to improve understanding of previous events. For example, for the Dig Tsho outburst flood in 1985, simulations suggested that the peak outflow at the lake outlet was about 5,600 $m^3 s^{-1}$ with peak flood depths downstream of 5–11 m, with the flood arriving at Nakchung 35 km downstream after about 1 h (Bajracharya et al. 2007).

Early warning systems have also been established for some locations, particularly to provide advance warning to construction projects. For example, an automated system was installed in 2001 for the Upper Bhote Koshi valley of eastern Nepal in support of a hydropower project (Ives et al. 2010). This included six water level sensors at a bridge near to the Nepal-China border to transmit data to the hydropower site by meteorburst telemetry. If critical thresholds were to be passed, warning sirens would be activated at five locations along the river. This approach was based on a similar previous system for Tsho Rolpa lake which was established in the 1990s (e.g. Fig. 11.4). Regular overflights and site inspections for lakes at risk are also a useful component in any early warning system (Ives et al. 2010).

Early warning systems are also sometimes used whilst engineering works are in progress to lower lake levels or stabilise the moraine. Some techniques which are used alone or in combination include controlled breaching of the dam, construction of outlet structures, removing water by pump or siphon, tunnelling beneath the moraine, stabilising slopes around the lake and protection or resettlement of areas at risk further downstream (Shrestha 2008; Ives et al. 2010). For example, following a GLOF event in 1994 at Luggye Tsho in Bhutan, the Raphstreng Tsho lake was also identified as a potential risk, and

(continued)

Box 11.2 (continued)

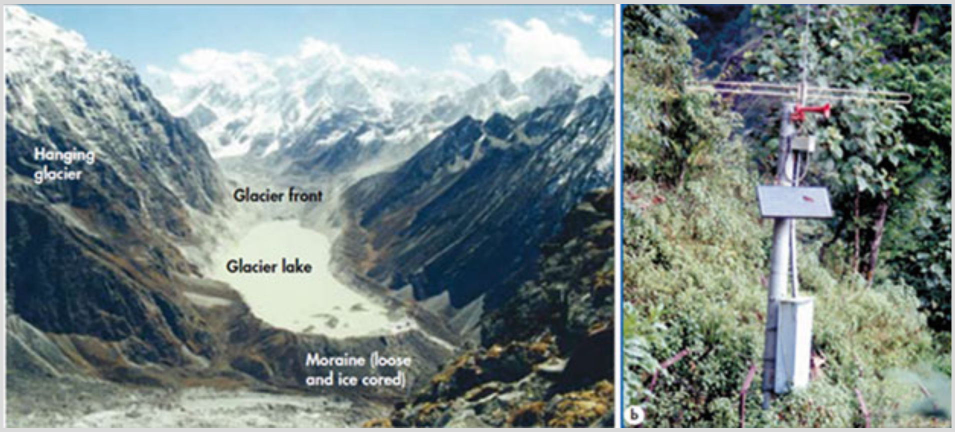

Fig. 11.4 General view of Tsho Rolpa glacial lake and an example of one of the automated warning sirens installed as part of the GLOF early warning system which operated from 1998 to 2002 (S. Joshi in Shrestha 2010 and Ives et al. 2010)

its level was successfully reduced by 4 m over 4 years. In Nepal, again based on a risk assessment, the level at Tsho Rolpa lake was also reduced by 3 m over 3 years by constructing an open channel and spillway at the dam (Matambo and Shrestha 2011).

11.3.2 Thresholds

When taking the decision to issue a warning, the criteria which are used depend on the type of emergency. For example, the case of overtopping of a dam wall or flood defence is perhaps the simplest to consider, providing that this does not result in a subsequent failure. As for other types of flash flood (see Chap. 8), threshold values are widely used and these are typically set on observed reservoir or river levels (for dams and levees respectively). Multicriteria thresholds are another option; for example for a dam considering factors such as the rate-of-rise of reservoir levels, river levels immediately downstream of the spillway, and rainfall depth-duration values.

Situations which potentially involve a breach or complete failure are rather more complex since the decision criteria also need to account for structural and geotechnical factors. For example, in addition to rainfall, level and flow information, some examples of the types of thresholds or triggers for implementing emergency measures can include (Australian Government 2009): earthquake occurrence, seepage flow, seepage turbidity, deformation and cracking, controls malfunction (flood gates and valves), controlled failures (fuse plugs), and hillside instability.

If there is a need to issue flood warnings, the locations to inform are typically based on pre-defined evacuation maps, using direct, community-based and indirect dissemination techniques, such as cell phone, sirens and the internet (see Chap. 6). In some organisations, decision support tools are used to assist emergency managers with deciding when to issue warnings and the priorities for evacuation of residential areas (see Chaps. 6 and 8). Some examples of past and current early warning systems for dams include:

- Nepal – an automated system for the Upper Bhote Koshi valley of eastern Nepal in support of a hydropower project (Box 10.2), including seven water level sensors transmitting data by meteor burst telemetry, and a number of warning sirens along the river (Ives et al. 2010)
- Norway – warning systems for the dams in two river basins based on four electronic circuits in the dam wall and four independent level recorders downstream of the dam. Interruption of a circuit or exceedance of a level threshold would cause civil protection authorities to be automatically notified and sirens activated if three of these independent systems were to be triggered (Konow 2004)
- USA – a temporary dam failure early warning system which was operated from 2003 to 2009 during construction work to upgrade Tuttle Creek Dam in Kansas. Dam breach simulations had suggested that approximately 13,000 people were potentially at risk and that the peak outflow in the event of a breach could exceed 10,000 $m^3 s^{-1}$. The instrumentation included strong motion accelerographs, piezometers, electrical resistance loops, inclinometers, Time Domain Reflectometry cables, remote controlled cameras, and a row of fixed lights on the dam crest and at the toe of the dam to detect major deformations at night. Six warning sirens were also installed with tone and voice alert capability (e.g. Fig. 11.2). Radio- and satellite-based telemetry was used and countdown timers were set to activate the siren system if there was no human response to alerts within 30–120 min. Some other aspects of the project included organizing tabletop and functional response exercises, publishing an evacuation plan and an extensive community outreach programme. The automated triggering components of the system were decommissioned in 2009 once the dam improvement works had been completed (Empson and Hummert 2004)

As these examples illustrate, sirens are probably the most widely used method for the dissemination of warnings whilst, as discussed in Chap. 6, other possibilities for the rapid dissemination of warnings include multimedia systems and cell broadcasting techniques.

More generally, for flood warning authorities, a number of other steps can help to improve the effectiveness of a warning system. For example, for dams, some possible preparatory actions for dealing with a dam emergency, should it occur, include (adapted from NOAA/NWS 2011):

- Geographic Familiarization – with major and high hazard dams in the warning area
- Procedural Familiarization – with models and data which could be used in an emergency

- Product Templates – preformatted warning message templates for watches, warnings and statements for dam failures
- Dam Failure Logs – for recording information from operators and others in dam failure situations
- Liaison With Local Emergency Services – close liaison with the local emergency services personnel regarding actions to be taken during dam failure situations
- Contact Numbers – ensure that forecasting office 24-h telephone numbers appear and are high on the list in all relevant Emergency Action Plans
- Emergency Action Plans – all relevant plans for the operations area should be readily accessible
- Dam Failure Drills – perform drills on an annual basis.
- Interagency Dam Failure Exercises – send representatives to inter-agency functional (table top) dam failure exercises held by dam operators

To provide more advance warning of the risk of flooding, it would also be desirable to use flood forecasting models. However, the development of techniques for forecasting the onset of dam or levee structural failures remains primarily an area for research. By contrast, if the risk is primarily from overtopping, then real-time flood forecasting models of the types described in Chaps. 5 and 8 often used to estimate reservoir or river levels; for example combining rainfall observations and forecasts, rainfall-runoff, reservoir routing and flow routing components. As discussed in Chap. 5, some forecasting systems also include the option to assess levee breach scenarios using real-time hydrodynamic models.

11.4 Summary

- Heavy rainfall, geotechnical and structural issues often combine to lead to the failure of dams or levees. The resulting outflows are one of the most devastating and rapidly developing types of flash flood. In high mountain regions, Glacial Lake Outburst Floods present a similar risk. Failures occasionally occur due to geotechnical or structural issues alone
- The main challenge in assessing the risk is usually to estimate the probability that a structure or natural barrier will fail. Often a typical failure mode and geometry is assumed and the magnitude and rate of outflow then estimated using hydrodynamic models or hydraulic formulae
- For dam breaks, hydrodynamic models are widely used to assess the extent of inundation at locations further downstream, based on the estimated inflows from a breach analysis. For levee breaches, two-dimensional models are typically used due to the need to represent flow depths, velocities and paths on the floodplain
- For flood response planning, a particular focus is often on the potential for loss of life and on streamlining monitoring, warning and response procedures. In many countries, dam operators, communities and civil protection and regulatory authorities are required to have response plans in place and to maintain up-to-

date risk assessments using techniques appropriate to the level of risk. Probabilistic techniques are increasingly used

- The inflows, levels and outflows at dams and glacial lakes, and levels in levee systems, are typically monitored using similar techniques to those for other types of flash flood. For monitoring structural or geotechnical conditions, many options are available including accelerometers, piezometers, pore pressure sensors and inclinometers. Techniques are also available for monitoring entire dam walls and levee sections using optical fibre systems, marker lights, remote survey methods, and time domain reflectometry
- Warning systems are typically established where the risk is high or a structure or lake already shows signs of problems. They also play a valuable role whilst engineering works are being performed. Typically warning thresholds are based on telemetry observations for reservoir and river levels and from structural and geotechnical monitoring equipment. However, techniques for forecasting the potential locations and extent of failures remain an area for research

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Chapter 12
Research

Abstract The flash flood warning process typically includes monitoring, forecasting and warning dissemination components. With current systems, there are many opportunities for improvements throughout this chain, particularly in the accuracy of observations and forecasts and the efficiency of warning procedures. This chapter highlights a number of recent developments in these areas, including phased array weather radars, wireless sensor networks, adaptive sensing techniques and the provision of warnings to road users. This includes a discussion of some of the challenges in translating research ideas into operational practice and the role that hydrometeorological testbeds can play in this process. Some current research themes in rainfall and flood forecasting are also described which are of particular interest for flash flood applications, including the communication of probabilistic information to end users.

Keywords Research • Hydrometeorological testbeds • Precipitation measurement • Catchment monitoring • Rainfall forecasting • Flood forecasting • Flood warning • Probabilistic forecasts • Ensemble forecasts

12.1 Introduction

In recent years there have been many improvements in the methods used in flash flood warning systems. These have typically been driven both by research findings and increasing political and public pressure to improve and extend the service provided; for example, to fast response upland catchments and for types of flooding problems perhaps not considered in the past, such as debris flows, urban drainage issues and potential dam and levee failures.

Allied to this there has been an increasing emphasis on obtaining a better understanding of the socioeconomic aspects of the warning process. In some cases this has built on experience gained with other types of fast developing natural hazards, such as tornadoes and earthquakes. For example, some potential areas in common

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Table 12.1 Some examples of previous and ongoing collaborative research studies with a flash flood component or emphasis

Name	Participants	Project description/objectives
CIFLOW (2000-ongoing)	Led by NOAA with multiple local, state, regional, academic and federal partners, and emergency management agencies	"The Coastal and Inland-Flooding Observation and Warning (CI-FLOW) project is a prototype system combining observations, weather and water models and decision support tools to help bridge the gap and predict total water levels in coastal areas" http://www.nssl.noaa.gov/projects/ciflow/
HyMeX (2009–2020)	International Scientific Steering Committee with representatives from many European countries and further afield	To improve understanding of the water cycle, with emphasis on extreme events, by monitoring and modelling the Mediterranean atmosphere-land-ocean coupled system, its variability from the event to the seasonal and interannual scales, and its characteristics over one decade (2010–2020) in the context of global change, and to assess the social and economic vulnerability to extreme events and adaptation capacity http://www.hymex.org/
IMPRINTS (2009–2013)	Canada, France, Italy, Netherlands, South Africa, Spain, Switzerland, UK	To contribute to the reduction of loss of life and economic damage through the improvement of the preparedness and the operational risk management of flash flood and debris flow generating events, as well as contributing to sustainable development through reducing damages to the environment http://www.imprints-fp7.eu/
Floodsite (2004–2009)	Europe-wide	An interdisciplinary project which integrated expertise in flood risk management – including flash floods – from the physical, environmental and social sciences, as well as in spatial planning and management, and which included over 30 research tasks across seven themes, with pilot applications in several European countries http://www.floodsite.net

include the design of warning messages, approaches to dealing with uncertainty, and the impacts of false alarms.

Due to the wide range of techniques used, research on flash floods is increasingly performed as part of multidisciplinary studies (e.g. Table 12.1). Typically these combine the skills of meteorologists, hydrologists, remote-sensing specialists, social researchers and other groups. Sometimes there is also the opportunity to evaluate techniques as part of long-term field experiments, such as the Cévennes-Vivarais Mediterranean Hydrometeorological Observatory in France (http://www.ohmcv.fr/) and the Hydrometeorology Testbed program in the USA (Box 12.1). For more than a decade, the summer and winter Olympics have also been used for field trials into nowcasting and other techniques (e.g. Wilson et al. 2010).

Box 12.1 Hydrometeorology Testbeds (HMTs), USA

Since 2000, the U.S. Weather Research Program has provided funding and operational support for a number of weather-related testbeds to assist with the transition of new tools and techniques into operational use (http://www.esrl.noaa.gov/research/uswrp/testbeds/). The topics covered include hurricanes, precipitation, hazardous weather, societal impacts, Numerical Weather Prediction and satellite data assimilation. For extreme precipitation, the Hydrometeorology Testbed (HMT) was established in 2003 to perform research into weather conditions that can lead to flooding and other hydrological impacts (Ralph et al. 2005; http://hmt.noaa.gov/). Some key objectives (NOAA 2010b) include the development of improved techniques for:

- Monitoring precipitation
- Predicting precipitation
- Determining the type of precipitation (i.e. rain or snow?)
- Coupling precipitation to what happens on the surface: snow pack; soil moisture; runoff; flooding and debris flow
- Developing decision support aids: providing not just more information to the front line forecasters and other users, but better information for decision making
- Verification: building credibility in the new products and services

The program is led by the Water Cycle branch of the Physical Sciences Division at NOAA's Earth System Research Laboratory (ESRL) in Boulder, Colorado, and includes a number of other NOAA agencies, the U.S. Geological Survey, universities, and local stakeholders.

Several sites across the USA have been selected to cover a wide range of typical climatic conditions, and these include the following locations:

- HMT-West (established in 2004)
- HMT-Northwest (established in 2009)
- HMT-South East Pilot (from 2013)
- Mini-HMTs–Arizona and Colorado (established in 2008 and 2009 respectively)

For the HMT-West and Northwest sites, field campaigns are performed in the winter (cool season) months whilst, for the HMT-South East site, the focus is for the summer months (warm season), and in particular on the impacts of tropical storms and hurricanes. Improved mesoscale models and new decision support tools are also being developed and evaluated in a pre-operational setting.

The first full-scale field campaign was for HMT-West in the winter of 2005/2006 (Fig. 12.1). This site is focussed on areas within and around the American River basin, which is situated between Sacramento and Reno on the western slopes of the Sierra Nevada and has a significant flood risk.

(continued)

Box 12.1 (continued)

Fig. 12.1 Illustrations of some of the instrumentation deployed as part of the HMT-West field campaigns. From *top left clockwise*: optical disdrometer; snow-level radar; mobile atmospheric river observatory; C-band scanning radar. The mobile observatory includes a Doppler wind profiler (*front of trailer*), an S-band precipitation profiler (*middle of trailer*) and a GPS antenna (*roof of control room*) (http://www.esrl.noaa.gov/psd/atmrivers/, Cifelli 2010)

For example, the instrumentation deployed for the 2010/2011 winter season included a C-band scanning Doppler radar, eight UHF wind profilers, seven S-band precipitation profilers, approximately 40 GPS humidity sensors, and six impact and optical disdrometers.

As with the other sites, there is also an extensive network of existing river level, raingauge and other instrumentation operated by the National Weather Service, the U.S. Geological Survey and as part of local flood warning (ALERT) systems. Outputs are also available from the existing National Weather Service NEXRAD S-band weather surveillance radar network. The project website provides researchers and operational staff with access to current observations during field campaigns and to archives of outputs from previous years (http://hmt.noaa.gov/).

For the HMT-West site, some key developments resulting from the observation campaigns and subsequent research include:

- Atmospheric Rivers – improved understanding of this key atmospheric feature which often leads to extreme rainfall and flood events in the western USA, and the development of decision support tools and mobile observatories

(continued)

Box 12.1 (continued)

to assist with monitoring and identifying these conditions (Neiman et al. 2009); see Box 4.1 for further information

- Non Bright Band Rain – identification of a shallow rainfall process in orographic cloud that occurs without apparent contribution from ice processes above the freezing level (Martner et al. 2008). Observations suggest that this accounts for about one-third of all rainfall in coastal California, including some moderate to heavy precipitation events, but that it is not well represented in weather forecasting models and is also the cause of major errors in weather radar derived precipitation estimates
- Howard Hansom Dam – operational support to the US Army Corps of Engineers (USACE) via the Seattle Weather Forecast Office during a potential dam failure crisis. This included deployment of additional raingauge telemetry, vertically pointing Doppler radars for snow level observations, and mobile atmospheric river monitoring observatories, and the provision of customised daily weather forecasts (White et al. 2012)
- Snow level and extreme precipitation – development and demonstration of new forecast verification measures and ensemble forecast performance measures (Ralph et al. 2010; White et al. 2010)

In particular, the findings on atmospheric rivers have led to improvements in forecasting techniques for extreme precipitation in the western USA (http://www.esrl.noaa.gov/psd/atmrivers/).

As new techniques are developed in each region, they are progressively brought into operational use. Based on the field campaigns, issues with the performance and coverage of existing observations systems are also identified and fed into improvements programmes for weather radar, raingauge, river level, snow observation and other networks.

For example, in California, one practical outcome has been the Enhanced Flood Response and Emergency Preparedness (EFREP) program led by California's Department of Water Resources, NOAA, and Scripps Institution of Oceanography (Ralph and Dettinger 2011). This is implementing key findings from the HMT-West study on atmospheric rivers and includes long-term deployment of four coastal atmospheric observatories, ten snow-level radar profilers and a state-wide network of soil moisture and GPS water vapour sensors, with 93 new field sites established between 2008 and 2012.

At the coastal sites, both observations and mesoscale forecasts are compared with pre-defined thresholds which help to identify when an atmospheric river is occurring and to assess its strength and orientation. Comparisons between the observed and forecast variables also help forecasters to evaluate how well the mesoscale model is predicting atmospheric river conditions at each site. A simulated atmospheric river event was also used as the basis for a severe winter storm scenario developed for use in state-wide emergency planning and response studies in California (Dettinger et al. 2011).

The translation of research into practice is increasingly facilitated by the availability of open-source (community-based) software and data management tools (e.g. Vasiloff et al. 2007; Roe et al. 2010). Typically these allow models and datasets from different providers to be combined in a seamless way. Chapter 3 provides further examples (e.g. CUAHSI, OpenMI). There are also a number of ongoing World Meteorological Organisation (WMO) initiatives to standardise measurement, modeling and data exchange techniques (e.g. World Meteorological Organisation 2007, 2008a).

This chapter describes a number of recent developments in the field of flash flood warning and forecasting. In the space available, it is only possible to discuss a selection of techniques and further information is provided in the references cited. It is also worth noting that in some cases it can take several years or flood seasons before a promising new approach is used operationally. A key reason for this is usually the need to ensure that any new procedures are fully tested and integrated into operational procedures (e.g. Table 12.2). Extensive consultations are usually also

Table 12.2 Some typical stages in translating research ideas into operational practice for software- and hardware-related developments in flash flood forecasting and warning

Stage	Typical tasks
Establish user requirements	Consultations with key users, workshops, demonstration of prototype techniques etc., plus a review of policy drivers, regulatory requirements, recent research, and technical options
Agree a development plan	Develop programme and specifications, define likely resource requirements (staff, financial etc.), obtain initial funding and management approval, establish a communication plan, identify suitable users/locations for pre-operational testing
Pre-operational testing/ proof of concept	Establish expert user group (including key stakeholders), set up systems, establish procedures, establish evaluation criteria, further development/tuning of prototypes as appropriate, seek wider feedback on the proposed approach
Evaluation and detailed design	Review of findings, consultations with key stakeholders, further development as appropriate. Then, either decide not to proceed or continue as required with updates to the development plan, identification of sponsors, obtaining budgets and approvals, developing an implementation plan, resolving any remaining licencing, copyright, intellectual property right or similar issues, developing monitoring, verification and reporting tools (if appropriate), establishing memoranda of understanding (or similar) between key partners, and completing environmental and health and safety assessments
Implementation	Finalise the concept of operations, confirm interagency agreements, procurement and installation of systems, finalise support arrangements (e.g. 24/7), integration into operational procedures, parallel running with existing systems for an initial period, finalise communication, training and operations and maintenance plans, public awareness raising activities, and confirm arrangements for monitoring and evaluation
Operations	Training, maintenance, support, repairs, upgrades, performance monitoring, routine and post-event reporting, development of research proposals for future improvements etc.

required with key users regarding the benefits and implications of any new approach. If significant investments are required, these may need to be justified using multi-criteria or cost-benefit analyses (see Chap. 7); for example, additional funding may be needed for computing infrastructure, observation systems, staff training and resources, or to upgrade research software and hardware to a fully operational state.

A balance therefore needs to be maintained between introducing new techniques and the associated risks of failing to provide accurate and timely warnings when a flash flood occurs. For example, NOAA (2010a) suggests the following six guiding principles when considering beginning or changing an existing product or service: mission connection, life and property first, no surprises, the stakeholders own the data, equity, and maintain and explain the routine products. Here, mission connection is ensuring that the product or service is consistent with the overall objectives of a flood warning service. However, more generally it is worth noting that in many cases there are often a number of 'quick-wins' and other improvements which can be adopted rapidly and at minimal cost.

12.2 Monitoring

12.2.1 Precipitation Measurement

Measurements of rainfall are a key input to many flash flood forecasting and warning systems. Chapter 2 describes the main techniques which are used, including raingauges, weather radar networks, and satellite precipitation estimation algorithms. Multi-sensor approaches are also increasingly used and combine the outputs from all three approaches with those from other sources, such as lightning detection systems, GPS humidity sensors and Numerical Weather Prediction models.

Many of the current developments in precipitation measurement focus on improvements to these existing approaches. For example, even for long-established methods such as raingauge monitoring, developments continue to occur, such as the increasing use of impact and hot-plate gauges (see Chap. 2). More radical solutions have also been proposed such as the derivation of real-time estimates of rainfall based on wiper speeds and water-clearance characteristics from the windscreens of cars and other vehicles (Haberlandt and Sester 2010).

For weather radar observations, some current areas for development include exploiting the benefits from dual polarization radar and the use of X-band radars (e.g. Boxes 2.1 and 10.1). For satellite precipitation products (see Sect. 2.4), research continues on how to make best use of the outputs from the space-borne precipitation radar carried on the TRMM satellite, and on ever more sophisticated algorithms combining microwave, infrared, and visible wavelength outputs from a range of sensors on both geostationary and polar orbiting satellites.

For all techniques, the issue of uncertainty estimation is a key topic, both to provide users with information on how reliable outputs are, and potentially as part of a move towards a more risk-based approach to decision-making (see Sect. 12.4.2). This topic is particularly important for multi-sensor products due to the need to combine outputs from different systems and organisations, and some weather radar products now routinely include quality indices or ensemble outputs (see Box 2.2).

Another current area of interest is the use of weather radar reflectivity outputs as part of the data assimilation process for mesoscale and convective-scale weather forecasting models. In particular, as noted in Chaps. 2 and 4, the distinction between observations and model outputs is becoming increasingly blurred, with model outputs widely used to help with the interpretation of satellite, weather radar and other observations.

Compared to these ongoing improvements, the development of new observation techniques is comparatively rare. However, some approaches which show potential for use in flash flood applications include phased array weather radars, adaptive sensing techniques and the use of existing microwave communication links to estimate rainfall. The new Global Precipitation Mission (GPM) is also already providing an impetus for research into improved approaches for satellite precipitation estimation. The following sections present examples of recent research in these areas and highlight some of the likely benefits for flash warning flood applications.

12.2.1.1 Microwave Links

When microwave radiation is transmitted between two locations, the signal received is attenuated if it passes through rainfall and other types of precipitation. This then provides an indication of the path-averaged rainfall intensity in a given period. This approach is of course closely linked to the principle of operation for weather radar, although that makes use of the backscattered or reflected signal.

Research experiments using single or dual-frequency microwave links have been performed for more than a decade (e.g. Ruf et al. 1996; Rahimi et al. 2004). The results typically show potential for rainfall estimation with the option to make observations at lower elevations than is possible with a weather radar. Typically the signal is transmitted over a distance of several kilometres and – for a given transmission frequency – the attenuation is influenced by a number of factors, including the rainfall extent, drop size distributions, and moisture on the antennas.

In early research the intention was that purpose-made links would be built. However, with the huge increase in mobile phone usage in many countries, an extension of this approach has been to investigate whether the tower-to-tower (backhaul) transmissions from cellular phone networks could be used instead (e.g. Leijnse et al. 2007; Zinevich et al. 2010).

Again, results show potential although some other factors to consider are that some operators use lower frequencies for longer links (with the attenuation depending on the frequency used) and that the geometry of the links is not optimized for rainfall detection, requiring some spatial interpolation of the outputs. If the issues of attenuation and reliability can be solved, then a key advantage will be the ability to provide spatially averaged rainfall observations using an already well developed infrastructure. This is likely to be particularly useful in areas not currently well served by raingauge or weather radar networks, and in urban areas with a good coverage of cell phone towers.

12.2.1.2 Global Precipitation Mission

The joint US/Japanese Tropical Rainfall Measuring Mission satellite or TRMM (http://trmm.gsfc.nasa.gov/; http://www.eorc.jaxa.jp/TRMM/) was launched in 1997 with a field of view between latitudes of approximately 35° north and south (see Sect. 2.4). The sensors on board included the first operational space-borne precipitation radar and the outputs have since been used for numerous research studies, including some flash flood applications.

The successor to TRMM is the Global Precipitation Measurement (GPM) mission (http://pmm.nasa.gov/GPM/). This will provide global coverage from a core satellite in low earth orbit combined with a constellation of new and existing research and operational polar orbiting satellites with passive microwave sensors. In addition to a multi-channel microwave radiometer and other instruments, the core satellite will carry a dual-frequency precipitation radar operating in the K_u and K_a bands (wavelengths ~2 and ~0.8 cm respectively) with a horizontal resolution at the ground surface of approximately 5 km. The outputs from this radar will serve as a reference for real-time calibration of the microwave sensors on the other satellites in the constellation.

Compared to the TRMM programme, this combined network will be able scan more frequently and view higher latitudes, and the radar will be better able to measure light rain and snowfall (Hou et al. 2008). The dual-frequency approach should also provide the ability to sample drop size distributions. The scheduled launch year for the core satellite is 2014 and an extensive network of ground-based monitoring stations will be operated to assist with validation of the outputs from the full constellation. These sites (both new and existing) will be located at a range of different latitudes in Europe, the Americas, Asia and Africa, and typically make use of dense raingauge networks, disdrometers, weather radars and other instrumentation.

In another development, both NASA and the European Space Agency have plans for the launch of space-borne Doppler radars in the next few years as part of other missions. The next generation of geostationary meteorological satellites (e.g. GOES, Meteosat) will also include a lightning mapper capability. All of these techniques are potentially of use in flash flood applications for earlier detection of storms and more frequent and accurate measurements of rainfall.

12.2.1.3 Adaptive Observation Strategies

With most current rainfall observation systems, the spatial coverage and temporal resolution is decided at the design stage and cannot be varied in real-time other than in certain cases; for example by selecting a different scan strategy for a weather radar, or using a rapid scanning mode for a geostationary satellite. The use of reconnaissance aircraft in the USA during hurricanes provides another example, in which meteorological conditions are sampled using on-board sensors and dropsondes.

The use of ground-based mobile sensors is another possibility; for example, by deploying portable weather stations, radiosonde launchers and other instruments to areas at risk and varying the schedule for radiosonde launches; for example, during fire fighting operations (e.g. Stringer 2006). As discussed in Box 12.1, mobile atmospheric river observatories have also been used in the USA to assist with operational decision making related to flooding, and mobile observatories are used in Taiwan to assist with providing warnings for debris flows once a typhoon warning has been received (see Chap. 9). In the related area of river monitoring, rapidly deployable river level monitoring platforms are used at some sites in the USA (see Box 3.1).

More generally, since the 1990s, an adaptive observation or targeting approach has been actively explored as part of research into data assimilation in both atmospheric and ocean forecasting models (Langland 2005). For example, remotely controlled drones (UAVs) are increasingly used in mesoscale meteorological experiments (e.g. Houston et al. 2012) and could potentially be used more routinely. Another option would be to deploy driftsondes on demand from weather balloons flying at high altitudes.

For example, the US National Research Council (2002) suggests that, as capabilities improve 'it may become possible to place weather radar systems on station at a variety of altitudes, for an extended duration'. Some other options could include re-routing commercial airliners carrying on-board meteorological sensors (see Sect. 2.5) and widening the equipment carried to include small lightweight weather radars. Wider operational use could also be made of mobile weather radars; for example, as is already done each winter in southern California to help to provide warnings for debris flows from areas affected by wildfires (see Box 9.1).

The development of more automated techniques is another active area for research and is often called adaptive or agile sensing. A key example is the use of adaptive radar networks to focus monitoring effort on the areas of fastest development in thunderstorms, tornadoes and other rapid-onset events. For example, with several radars installed around a city, the combined scanning strategy could be coordinated to track a thunderstorm as it passes through the area, providing detailed three-dimensional information on the precipitation and wind fields (see Box 12.2). For the future, there are also likely to be improvements in the targeting of meteorological sensors carried on polar orbiting satellites.

Taken together, these various techniques have the potential to focus ground-based, atmospheric and satellite observations towards the areas of greatest risk at any given time, with the aim of providing earlier and more accurate warnings. As discussed in Sect. 12.3, this potentially opens the way to a more interactive approach to forecasting extreme weather, allowing meteorological forecasters to target model runs and observations towards the most potentially destructive storms.

Box 12.2 Phased Array Radar

The first aircraft tracking radar systems to be developed in the 1930s relied on a rotating antenna dish to provide 360° coverage about the monitoring site. This principle is still used in most weather surveillance radars nowadays.

However, since the 1970s phased array radars have been extensively used for military applications. These consist of solid state flat- or curved-panel devices in which scanning is performed electronically rather than mechanically. Each panel is made up of hundreds or thousands of individually controlled transmit-receive elements. The width and direction of the transmitted beam is then a function of the interactions between the phase and timing of the signal from each element. This type of radar is also sometimes described as an 'e-scan' or 'electronically scanned' device.

The potential of phased array radars for meteorological applications was first identified in the 1980s and 1990s in both the USA and Europe although cost was a major obstacle to doing research with the technology at that time (e.g. Meischner et al. 1997). This had to wait until 2003 when an S-band phased array testbed was set up at the National Severe Storms Laboratory (NSSL) in Oklahoma as part of a multi-agency research project (OFCM 2006; Zrnic et al. 2007; http://www.nssl.noaa.gov/). The NSSL testbed has since been used in numerous research studies as well as for developing and evaluating the technology further.

Compared to current systems, phased array devices should lead to greater reliability and lower maintenance costs. Considerable cost savings could also be realized by using the same instruments for meteorological, aviation and other civilian applications. For flash flood, tornado and other fast-developing events, there is also the benefit of faster volume scans at a higher resolution over a wider range of scan angles and elevations. For extreme weather events, this provides the possibility to 'facilitate the earlier detection of significant storm development, convergence, microburst precursors, wind shear, and hail signatures' (Heinselman et al. 2008). More generally there is the potential for improvements in the data assimilation process for mesoscale weather forecasting models.

In addition to the large, long-range S-band technology being researched at NSSL, small, short-range, low cost X-band devices are also being researched

(continued)

Box 12.2 (continued)

(McLaughlin et al. 2009; http://www.casa.umass.edu). With a range of only 40 km, these might be used for infilling gaps in regional or national radar coverages and/or for observations of very low altitude boundary layer phenomena. In operational use, a typical configuration might be to use three to four panels per site to provide 360° coverage. Each panel would measure about 1 m^2 and be fully self-contained in the sense of including all of the transmitting, receiving, beam steering, data acquisition, signal processing, communication and power conditioning electronics required (McLaughlin et al. 2009). Typically, the aim would be to complete volume scans in less than 1 min, each panel covering between 90 and 120° in azimuth and (in an infill deployment) elevation angles up to about 30°. At least two such systems are currently under development by commercial organisations.

Due to the small size and power requirements, the small X-band devices could be installed in cities and other urban areas on buildings and masts at a number of locations (Fig. 12.2). Adaptive or agile sensing strategies could be used as part of a distributed or centrally-controlled network in order to achieve fast (<1 min) updates on volumes of rapid storm development, such as thunderstorms and tornadoes (McLaughlin et al. 2009).

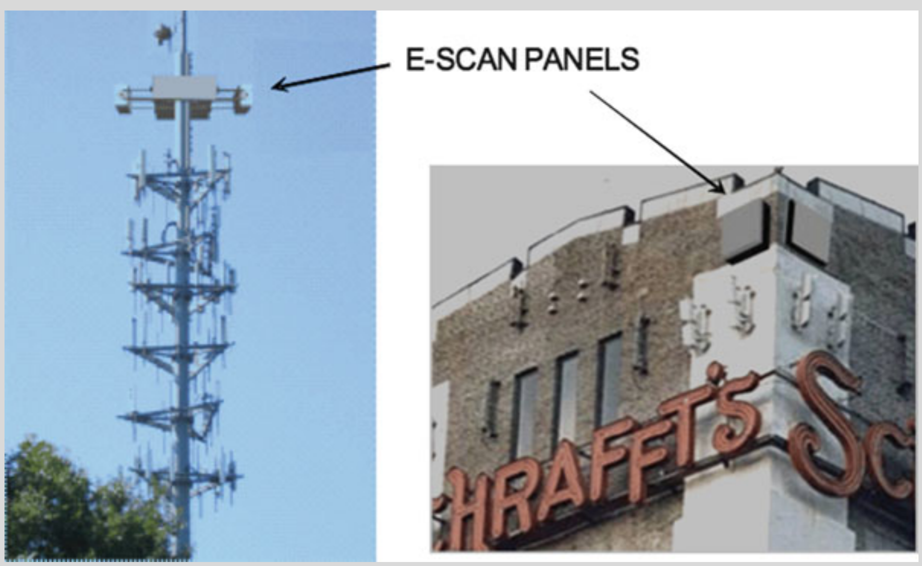

Fig. 12.2 Artist's renditions of two potential electronically scanned (e-scan) radar designs as they might appear when mounted on existing infrastructure, such as a cellular communications tower or the side of a building. The tower-mounted example shows a phase tilt deployment (electronically scanned in azimuth, mechanically in elevation) whilst the building-mounted example shows a phase-phase deployment (electronically steered in both azimuth and elevation) (McLaughlin et al. 2009)

12.2.2 *Catchment Monitoring*

River level measurements and catchment soil moisture estimates are key inputs to many flash flood forecasting and warning systems, and snow observations are sometimes used in colder regions.

As discussed in Chap. 3, automated river monitoring techniques have been used for decades and completely new techniques are comparatively rare. However, some methods which have been adopted widely in recent years include the use of Acoustic Doppler Current Profilers (ADCP) for river flow gauging, and of non-contact ultrasonic and radar sensors – situated above the water surface – for measuring water levels. Indeed, ADCP techniques have rapidly moved from being primarily a research tool to the standard approach in many organisations.

For soil moisture estimates, due to the large spatial variations in values, model-based estimates tend to be used more frequently than direct observations. However, remotely sensed values by satellite show potential for wider use, complemented by ground-based observations to assist in calibration of the outputs. Similar considerations apply to snow observations. Again, Chap. 3 discusses some techniques which have made the transition into operational use in the past one to two decades and others which show potential. These include vertically-pointing snow-level radars (see Box 12.1) and capacitance and temperature-based sensors for automated monitoring of soil moisture. However, as with precipitation measurement systems, research often consists of continuing improvements to existing systems, although the following sections discuss some newer ideas which show potential for flash flooding applications.

Wireless Sensor Networks

Recent developments in computer and telecommunications systems mean that it is now possible to produce small, low-cost wireless devices with in-built computer processors and environmental sensors. These are typically battery powered and communicate with each other and a nearby base station using on-board radio transmitters and receivers. The base station or gateway then uses any convenient telemetry method to send information onwards to end users.

So-called pervasive or grid networks of this type have been used in a number of environmental and engineering applications, including bridge monitoring, habitat surveys and air quality monitoring (e.g. Basha et al. 2008; Hoult et al. 2009). Their low cost and small size typically allows a much denser network to be installed than with a conventional approach, which is also generally resilient to the loss of any single instrument.

For flash flood applications, some potential uses include river level monitoring, measuring conditions in stormwater drainage networks (e.g. Stoianov et al. 2007), and geotechnical monitoring for debris flows, dams and levees. In river applications, sensors are typically the size of a housebrick and installed on river banks, bridges, or the river bed. For example, water levels could be recorded at several locations along a river reach as well as at a number of key locations on the floodplain (e.g. Hughes et al. 2006). Wireless sensors could also potentially be used where the visual impact or risk of vandalism is likely to be (or already is) an issue when using more traditional river level recorders.

By using the network computing power, it is also possible to run flood forecasting models and evaluate the outputs against pre-defined thresholds. For example, this approach has been evaluated at several river test sites in the UK (Smith et al. 2009) using a Data Based Mechanistic (DBM) data-driven forecasting model with a probabilistic data assimilation component. Flood warnings would then be issued automatically to mobile phones or used to activate electronic signs or other automated equipment. Some potential applications include providing warnings to isolated groups of properties where a full flood warning service would not be justified, and developing a bespoke service for critical infrastructure operators, such as at power stations or water treatment works.

These techniques have also been trialed in the USA and Honduras (Basha et al. 2008) using flood forecasts computed using a multiple-regression approach based on rainfall, air temperature and level observations made using magnetic switch, resistance and pressure transducer sensors. River flows were then estimated from stage-discharge relationships. For example, at the Honduras test site, groups of sensors were linked to radio-telemetry base stations, transmitting over distances of more than 50 km.

River Gauging Techniques

Regular measurements of river flows (or 'spot gaugings') are an essential task for many river gauging sites to establish stage-discharge relationships (see Chap. 3). However, for flash flood applications, the rapid rise in river levels often means that there is insufficient time to accurately measure the highest flows or – in some cases – even to reach the site. There are also potential safety issues with working near to flood water.

These considerations have led to the search for safer, faster ways of measuring discharge. For example, one approach which has been under development since the 1990s is to use techniques which take sequences of digital images of a river surface. These are then processed to derive an estimate for surface velocities and flows (e.g. Creutin et al. 2003; Muste et al. 2008). This approach has also been used in research studies on debris flows (e.g. Arattano and Marchi 2008). Typically, measurements are made from cameras mounted at a safe distance above the highest likely water levels.

This technique, called Particle Image Velocimetry (PIV), was initially developed for laboratory use in industrial applications. However, for hydrological applications, the term large-scale PIV (or LSPIV) has been coined. The method relies on imaging of floating debris, foam, surface waves, turbulent eddies, sediment and other tracers on the water surface. Following image orthorectification, a statistical pattern-matching technique is typically used to infer the surface velocity distribution. The discharge is then estimated by making assumptions about the velocity profile based on theoretical or empirical techniques or previous observations at that location, and survey information for the river cross section profile.

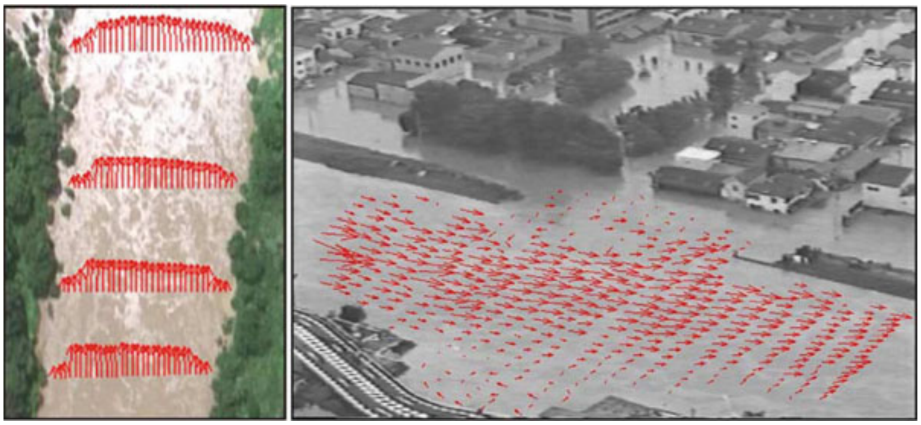

Fig. 12.3 Mean flow distribution during floods measured from helicopter (Japan): (**a**) cross section in the Katsura River (river width 90 m) and (**b**) flow distribution measured during a levee breach on the Shinkawa River (river width 80 m) (Fujita and Hino 2003; Muste et al. 2008)

Some potential challenges for river applications include low lighting conditions and a lack of suitable tracers in some periods. However, field experiments suggest that the approach provides a useful complement to conventional river gauging techniques, and often provides results of comparable accuracy (e.g. Fujita et al. 2007; Muste et al. 2008; Fujita and Muste 2011). The ability to visualize and analyse velocity fields is also useful for research into hydrodynamic modelling techniques for river and floodplain flows. For flash flood applications, the speed of measurement and the ability to monitor flows from a safe location are both of particular interest for measuring high flows. For example, based on results from an experimental fixed installation in a catchment in southern France (Le Coz et al. 2010), the approach was subsequently extended to a number of other key river gauging sites. Vehicle and helicopter based platforms provide another option (e.g. Fig. 12.3).

Another technique which has been evaluated – and does not require contact with the water surface – is the use of radar velocimetry. This relies on the reflections from wind- or turbulence-generated waves on the river surface, and options include various types of UHF and microwave-frequency Doppler and other devices (Costa et al. 2006; see Box 3.1 also). Again this technique shows promise, particularly for observations of high flows.

12.3 Forecasting

12.3.1 Rainfall Forecasting

Meteorological forecasts are used in many applications and this is therefore an active area for research. For flash floods, some recent and ongoing developments of particular interest include:

- Convective- and storm-scale models – Numerical Weather Prediction (NWP) models operating at horizontal scales of 1–4 km or less and able to represent the

development of storms and, in particular, thunderstorms. For example, the eventual aim could be to provide ensemble outputs every few minutes at a horizontal grid spacing of 0.25 km or less (e.g. Stensrud et al. 2009). Amongst other requirements, this will need new approaches to the parameterization of convective and turbulence processes
- Data assimilation – the use of higher resolution, more frequent observations to help to initialise atmospheric models, such as radar reflectivity, GPS humidity and radar refractivity observations, measurements from aircraft in their landing and take-off phases, and - for the future - adaptive sensing techniques using X-band and phased array weather radars (see Sect. 12.2)
- Forecast verification – a renewed interest in spatial verification techniques, appropriate to the latest generation of high resolution models, considering the shape, position, timing, size, spatial structure and intensity of storms and other features; for example, using neighbourhood ('fuzzy'), field deformation, object-oriented and scale decomposition approaches, with a particular emphasis on extreme (rare) events (e.g. Jolliffe and Stephenson 2011; Gilleland et al. 2010)
- Post-processing – the ongoing development of analogue, dynamic and statistical techniques to downscale model outputs to the scales of hydrological interest, and to calibrate the probabilistic content of ensemble forecasts (e.g. Jolliffe and Stephenson 2011)
- Reforecasts or hindcasts – the generation of archives of forecasts based on current model configurations, supported by reconstructions of weather radar, satellite and other historical observations to emulate the current approach to data assimilation
- Thunderstorm initiation – forecasting the onset and severity of severe convective storms using probabilistic nowcasting techniques combined with convective- and storm-scale model outputs and forecaster inputs, particularly for 0–2 h ahead forecasts (e.g. Wilson et al. 2010)

Many of these developments are linked to the introduction of higher resolution numerical weather prediction models and – as discussed in Chap. 4 – some meteorological services already use some of these techniques operationally (e.g. Box 12.3). Allied to these moves to finer scales is the need to find computationally faster solution schemes and improved methods for generating ensemble outputs, considering the uncertainty arising from the initial and boundary conditions and model structure, parameters and resolution.

Another area for research is the development of techniques to provide seamless ensemble forecasts at the full range of timescales, from observations through to short-, medium- and long-range forecasts. The resulting forecasts would include estimates of the uncertainty at all lead times and use a consistent set of post-processing and forecast verification techniques across all spatial and temporal scales. Under this scenario, multi-sensor precipitation products and nowcasts might drop away as distinct products.

As illustrated in Fig. 12.4, another key area is the development of decision support tools which both assist forecasters and make best use of their expertise in the forecasting process. For example, these could allow a forecaster to compare outputs

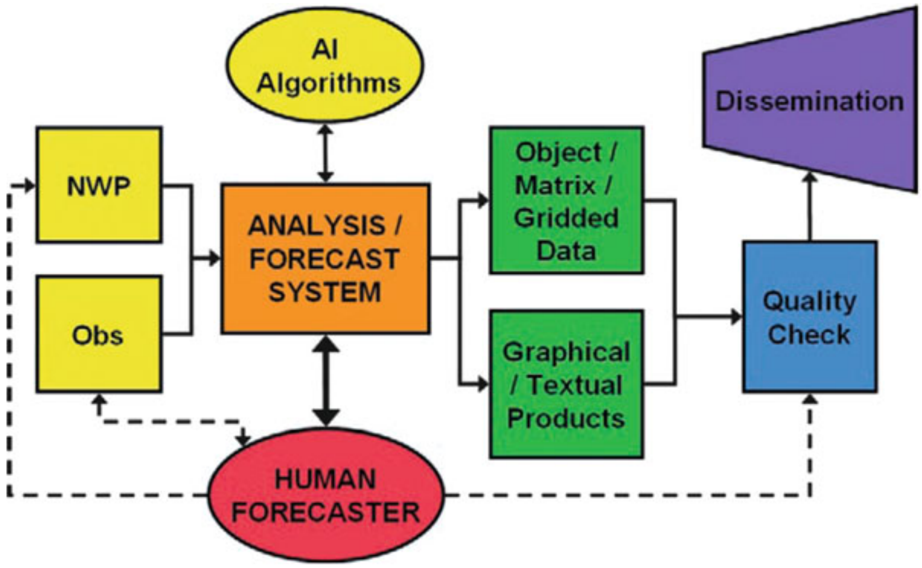

Fig. 12.4 One possible scenario for future forecaster inputs in the Meteorological Service of Canada. The interaction with the analysis/forecast system would be central to the forecast process. *Yellow boxes* represent various inputs, while *green boxes* represent various outputs. *Bold arrows* indicate that the main interaction is between the forecaster and the analysis/forecast system. The forecaster may also influence NWP models, observations, and quality checking (all shown as *dashed arrows*). Public reports of severe weather events are a special type of observation that could go directly to the forecaster (also shown as a *dashed arrow*) (Sills 2009; Sills et al. 2009)

from a multi-model ensemble, select the most appropriate model (or models) to use ('of the day'), adjust the inputs using an interactive map-based display showing current observations and forecasts, and then perform one or more revised analyses. Higher resolution forecasts could also routinely be generated in areas of particular interest, as is already done in some meteorological services in response to environmental disasters or military requirements.

More generally, forecasters could also decide how best to target adaptive observation systems (see Sect. 12.2), and guide the generation of ensembles depending on the areas of greatest uncertainty identified from current observations and model outputs (e.g. Langland 2005; Thorpe and Peterson 2006). Tailor-made ensemble forecasts could then be generated to meet the risk profiles and economic circumstances of different users and customers. Regarding issuing severe weather warnings, Stensrud et al. (2009) note that some key tasks could include examining 'three-dimensional storm and environmental analyses, assessing the plausibility of the probabilistic hazard forecasts, assessing system performance as spotter information and other verification data become available, looking for errors in the system that lead to inaccurate probabilistic hazard information, and issuing warnings as needed'. These techniques all have the potential to improve the accuracy and timeliness of rainfall forecasts and hence – in collaboration with flood forecasting staff – flash flood forecasts and warnings.

Box 12.3 Ensemble Flash Flood Forecasting Research, Southern France

For flash flood forecasting applications, the latest generation of mesoscale Numerical Weather Prediction models offer a number of potential advantages. For example, the outputs are better able to represent features such as convective storms and orographic effects, which can strongly influence where and when flash floods occur. More detail is also provided on the spatial distribution of rainfall with outputs typically available at a grid resolution of 1–4 km.

Within Météo-France, a non-hydrostatic mesoscale model (AROME) has been used operationally since 2008 (Seity et al. 2011). This has a grid scale of 2.5 km and provides hourly forecasts for lead times of up to 30 h ahead. It forms part of an operational suite of models which includes the ARPEGE global model. In AROME, a 3D-Var mesoscale data assimilation scheme is used, including observations from radiosondes, automatic weather stations, wind profilers, weather radar (Doppler winds and reflectivity), GPS humidity sensors, buoys, ships, aircraft and satellites (Vincendon et al. 2011). For example, Fig. 12.5 compares observed values and hindcast estimates of rainfall for the Gard flash flood of 2002, which was one of the most catastrophic events in southern France in recent decades (Delrieu et al. 2005). A nowcasting-capable version is also under development providing 12-h ahead forecasts every hour.

One particular use of AROME is for flash flood forecasting in the Cévennes-Vivarais area and the Var region of southern France. For this application, due to the uncertainties in precipitation forecasts, an ensemble forecasting approach offers a number of advantages. However, conventional approaches to the generation of ensembles are computationally intensive which can be a disadvantage in fast-evolving flash flood events. These considerations have led to the search for more computationally efficient methods which are also

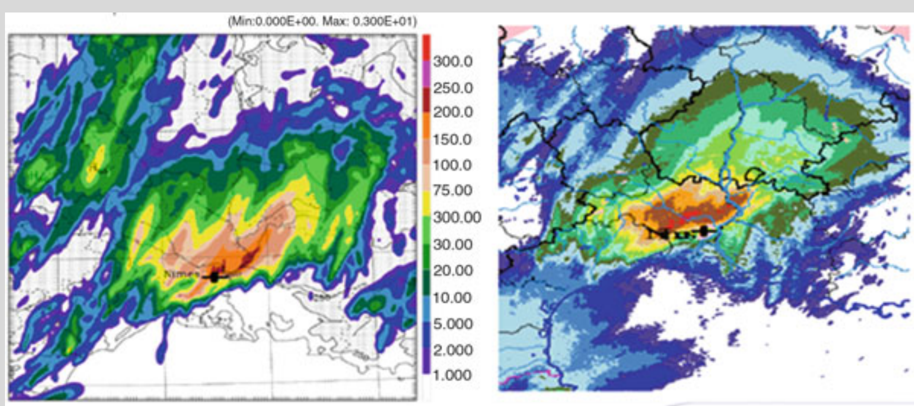

Fig. 12.5 Comparison of AROME and weather radar Quantitative Precipitation Estimates for the Gard flood event in 2002 (Carrière et al. 2011)

(continued)

Box 12.3 (continued)

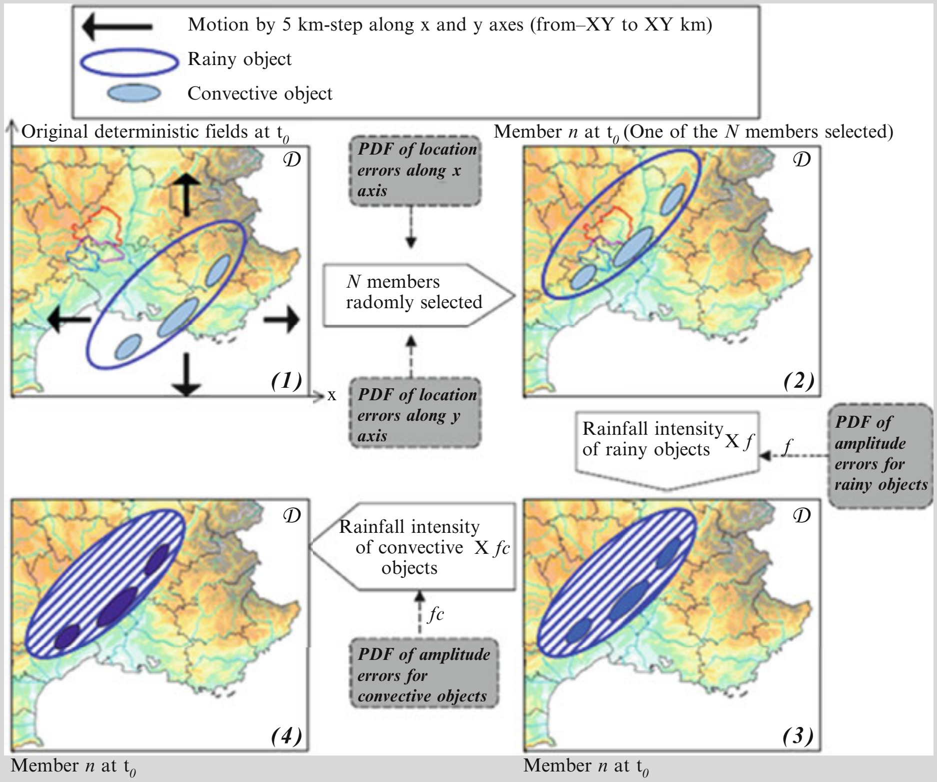

Fig. 12.6 Principle of the perturbation generation method at time t_0 (Vincendon et al. 2011)

more focussed on the scale and types of storms likely to cause flash flooding. In particular, it is desirable to take advantage of (and preserve) the mesoscale features observed by weather radar and satellite, such as the spatial organisation of convective cells.

In one method under development in Météo-France, an object-based approach is used to identify storm cells and then to generate ensemble members based on their key characteristics. The initial stage in the procedure is to develop an error model describing the performance of the deterministic AROME model over a number of historical events in terms of the structure, location and amplitude the precipitation field. For example, in comparisons with weather radar observations (Vincendon et al. 2011) it was found that thresholds of 2 and 9 mm h^{-1} could be used to delineate areas of rainfall and convective rainfall respectively.

The ensemble members are then generated by sampling from the probability density function of location errors, with modifications for amplitude and rainfall distribution errors (Fig. 12.6); for example generating 50-member ensembles allowing horizontal displacements of up to 50 km and amplitude factors of 0.5–1.5. A distributed hydrological modelling approach is then used

(continued)

Box 12.3 (continued)

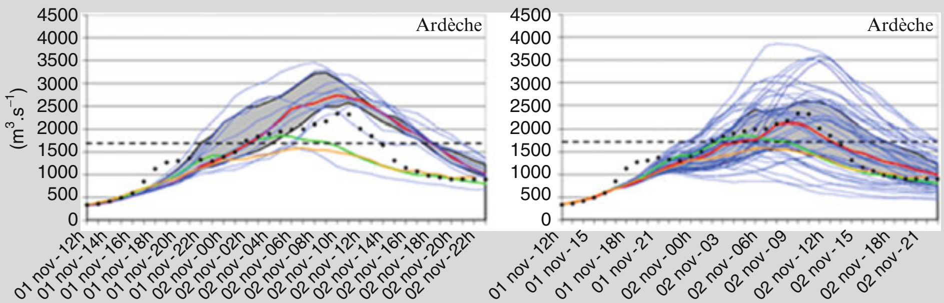

Fig. 12.7 Comparison of flood forecasts for the Ardeche at Vallon Pont d'Arc for an event on 2 November 2008 using an 11-member AROME ensemble and a 50-member ensemble derived using an object-based approach. The figures show the observed flows (*symbols*), ensemble median (*red line*), interquartile range (*shaded area*), deterministic forecast (*green line*), a forecast using radar rainfall observations (*orange line*), and the flood warning threshold level for this location (*dashed black line*) (Adapted from Vincendon et al. 2011)

to estimate flood flows. This couples the ISBA land-surface model (Noilhan and Planton 1989) and a version of TOPMODEL optimised for Mediterranean catchments (Pellarin et al. 2002); ISBA governs the overall budget among soil columns while TOPMODEL computes the sub-surface lateral water fluxes and spatial and temporal dynamics of the saturated areas using the watershed topography (Bouilloud et al. 2010).

Hindcasting analyses for two events in southern France in 2008 (Vincendon et al. 2011) showed that the ensemble median value outperformed the flows estimated from the deterministic AROME forecasts. The object-based approach also gave similar skill scores and other performance statistics to model runs using a more computationally-intensive approach which takes account of the uncertainties in both initial and lateral boundary conditions (Vié et al. 2011). The ability to generate more ensemble members (50) than was possible with the more computationally-intensive approach (11) also contributed to the performance improvements (e.g. Fig. 12.7). An object-oriented forecast verification technique (Wernli et al. 2008) was also used for evaluating the forecast performance in terms of the location, amplitude and structure of the precipitation field.

Current research includes evaluating the approach on more events, including observations made during the field experiments within the Hydrological Cycle in Mediterranean Experiment (HyMeX) project (http://www.hymex.org/), and considering additional sources of uncertainty, such as in initial soil moisture conditions and the hydrological model parameters. Shorter range X-band radars are also being evaluated to provide more detailed observations in areas where there are gaps in the national radar coverage and/or the data quality is poor (particularly in mountainous areas).

12.3.2 Flash Flood Forecasting

Due to the short time available, flood forecasts can be particularly useful when deciding whether to issue flash flood warnings. Typically, model outputs are used to assist with interpreting complex situations and issuing warnings earlier than would be possible from observations alone. This includes both general alerts using flash flood guidance techniques and site-specific warnings using rainfall-runoff and integrated catchment models.

For river forecasting models, data assimilation is widely used, and probabilistic techniques are increasingly used. However, these approaches are mainly areas for research for other types of flash floods such as ice jams, debris flows, and those caused by surface water and dam breaks. Chapters 8–11 describe a number of other techniques under development for specific applications. More generally, some current hydrological research themes relevant to flash flood forecasting include:

- Arid zones – assessing the flood risk and providing forecasts for the floods generated by isolated thunderstorms and other localized events and for which runoff processes differ markedly from in more temperate regions
- Data assimilation – the development of techniques for use with grid-based (distributed) rainfall-runoff and one- and two-dimensional hydrodynamic models
- Probabilistic forecasting – the development of ensemble and other approaches taking account of all sources of uncertainty, including model structural issues and initialization, modelling and forcing errors

For the first of these issues, some typical problems encountered in arid or semi-arid areas are (World Meteorological Organisation 2011):

- Highly localized rainfall, which may not be captured by raingauges, particularly if these are sparsely distributed
- Highly seasonal rivers, with a large range of discharge and level. These are difficult to measure with both structures or at rated sections by current meter, as channel conditions change during and after each flood event
- Ephemeral rivers, which exhibit considerable losses through the channel bed along lower reaches
- Major changes in the course of rivers and destruction of measuring devices by flood flows
- Problems of maintenance and performance of monitoring equipment in harsh conditions, especially dust and heat

This has required the development of new techniques both for assessing flash flood risk and issuing warnings, particularly for ungauged locations. For example, probabilistic techniques are increasingly used, as illustrated in Box 12.4. As noted in earlier chapters, other developments include the use of event-based distributed models which focus on overland flows (Yatheendradas et al. 2008) and of techniques for the design of raingauge networks in semiarid regions (Volkmann et al. 2010).

More generally, when using distributed models a key constraint is often the limited amount of real-time information available for data assimilation. Remotely sensed observations provide one possible way of overcoming this problem; for example by using satellite estimates of snow cover, snow water equivalent and soil moisture (e.g. König et al. 2001; Wagner et al. 2007). This updating problem is similar to the data assimilation problem in meteorology (see Chap. 4) and variational, ensemble Kalman filter and other approaches have been used for both flood forecasting and seasonal applications, using in-situ and/or satellite observations (e.g. Lee et al. 2011; Le Dimet et al. 2009; Liu et al. 2012; Ni-Meister 2008). However, for flash flood applications, satellite-based observations are still at a relatively coarse resolution compared to the scales of interest, although continue to improve (see Chap. 3).

Another consideration is the need to calibrate models using the same inputs as will be used in real-time, otherwise significant mass balance and other errors are likely to accumulate. Ideally this then requires long-term hindcasts representative of current systems and algorithms. Another key question is whether to assimilate the primary observations (e.g. satellite radiances) or post-processed values (e.g. soil moisture). For example, when using the processed values, these are closer to the actual variables used in a model; however, the use of raw data avoids dependence on the post-processing techniques used. Again, these are all active areas for research.

These issues are also relevant to real-time hydrodynamic modelling. This is particularly the case when models are used for inundation mapping since, in some cases, the flood extent covers several kilometres of river reach with few if any real-time river level observations available. There are sometimes also sudden changes in levels at structures such as weirs and surcharged bridges. Again this is a developing area with some possible options for obtaining more real-time information on floodplain levels including satellite altimetry (e.g. Giustarini et al. 2011) and distributed networks of wireless sensors (e.g. Neal et al. 2012); see Sect. 12.2.

As discussed in previous chapters, with all of these approaches, estimates of the uncertainty in outputs should be provided if possible, and the following classification scheme is useful to describe the types of methods which are available (e.g. Beven 2009):

- Forward uncertainty propagation – methods in which the uncertainty from individual sources is estimated. This is then propagated through the chain of model components which make up the overall flood forecasting model
- Probabilistic data assimilation – techniques which both reduce and provide estimates for the uncertainty as part of the assimilation process
- Probabilistic forecast calibration – the post-processing of model outputs to estimate the probabilistic content based on a statistical model of past forecasting performance at the gauge(s) and lead times of interest

Within the first of these categories, the use of ensemble rainfall forecasts is perhaps the best known example. In this approach, ensembles of typically 20–50 members are propagated through the flood forecasting component, providing an equal number of ensemble flood forecasts. In meteorology, the ensemble generation process (see Chap. 4) has been the topic of extensive research for more than two decades and is usually designed to provide individual members that are – in principle – equally likely. However, as discussed in Chap. 4, due to limitations on sample sizes and the sources of uncertainty considered, some additional post-processing is normally required to calibrate the probabilistic content if quantitative estimates are required. Section 12.4.2 discusses some situations where this may be desirable. Also, it remains an open research question whether there is any advantage in calibrating the ensemble rainfall inputs when a probabilistic data assimilation or forecast calibration approach is used for the outputs from a flood forecasting model. The following simpler forward uncertainty propagation approaches are other possible choices when only an indication of the uncertainty is required:

- Multi-model ensembles – ensembles generated by using the outputs from several models operated in parallel. This is sometimes called a poor-person's ensemble but is often useful for exploring the uncertainty arising from model structural issues
- Multiple inputs – the use of several types of observations and forecasts in a model in parallel to provide an indication of the uncertainty arising from these sources; for example, considering rainfall inputs based on raingauge and weather radar observations and nowcast and mesoscale model forecasts
- Time-lagged ensembles – outputs in which the deterministic forecasts for the previous few forecast runs are viewed alongside the current forecast to provide an indication of the variability and/or persistence in forecasts over time
- 'What-if' scenarios – assessments of the sensitivity of forecasts to factors such as future rainfall, control gate settings, and levee breaches; for example, assuming the following rainfall scenarios: no further rainfall, the rainfall continues as now, the rainfall will match one or more previous extreme events

Forward uncertainty propagation techniques are also useful for assessing the sensitivity of model outputs in off-line calibration studies; for example, to help to identify model limitations and possible requirements for model and telemetry improvements. For these types of studies, more computationally intensive techniques are often used, such as Monte Carlo approaches.

Another consideration is that often there are several different and possibly interdependent sources of uncertainty to consider, particularly at short lead times. For example, in addition to model structural issues and the uncertainty arising from rainfall forecasts, some other sources which might need to be considered include those arising from the model parameters, rating curves, and weather radar observations. When quantitative estimates of uncertainty are required, to avoid trying to specify these interactions, forward uncertainty propagation techniques are therefore typically best suited to the situation when there is one dominant source of uncertainty, such as at long lead times when the uncertainty in rainfall forecasts dominates. If model run times are an issue, some options for reducing the times taken include computer processor improvements, model configuration changes, statistical approaches (e.g. sampling or grouping of ensembles) and the use of model emulators.

Regarding the two other main approaches – probabilistic data assimilation and forecast calibration – Table 12.3 provides some examples in each category; however, many other techniques are under development and this is an active area for research (e.g. Beven 2009; Weerts et al. 2012). Also, it is important to note that some forms of data-driven models provide estimates of uncertainty directly as part of the forecasting process (e.g. Young et al. 2012). When using multi-model ensembles, another option is to combine the estimates using approaches such as Bayesian Model Averaging (e.g. Raftery et al. 2005).

As for deterministic flood forecasting models, the best approach to use typically depends on a range of factors (see Chap. 5). Typically these include the catchment response time, the level of flood risk, the warning lead times required, the operational requirements for probabilistic information, budgets, and the computing resources required (e.g. Beven 2009; Sene et al. 2012).

In particular the dominant sources of errors often vary with the forecast lead time – as illustrated in Box 8.3 for example – and this can strongly influence the choice of method. For example, when using river gauge observations for data assimilation, the reductions in uncertainty usually tail off beyond the catchment response time as the information content of the observed flows decreases. There may therefore sometimes be advantages in using a probabilistic data assimilation approach at shorter lead times combined with a forecast calibration approach at longer lead times. Also, in case of gauge failure, a forward uncertainty propagation method could be operated as a backup to continue to provide an indication of the uncertainty until the gauge is reinstated; however some probabilistic data assimilation approaches are tolerant to data loss and provide another possible option.

These are all developing areas and ideas are still evolving about the most appropriate techniques to use. As in many other areas of flash flood forecasting the choice of method should be tailored to the specific application and Sect. 12.4.2 discusses this topic further.

Box 12.4 Flash Flood Research, Negev Desert and Dead Sea Region, Israel

With an area of about 10,000 km^2, the Negev Desert occupies more than half of the land area of Israel although is relatively sparsely populated. The climate ranges from semi-arid in the north to arid in the south, with an average annual precipitation ranging from about 350 to 25 mm (Kahana et al. 2002).

The main rainfall season is from October to May although this can extend into September and June. Rainfall is highly variable between years and the coefficient of variation for annual values exceeds 0.35–0.40 (Goldreich 1995). The main topographical feature is the central Negev Mountains range which rises to a height of about 1,000 m. The six drainage basins rising in these mountains cover most of the Negev and drain towards the Mediterranean and Dead Sea areas. Smaller basins to the south also drain into the Gulf of Aqaba.

(continued)

Box 12.4 (continued)

Flash floods occur in most years and present a risk to hikers and vehicles and occasionally to villages in the region. An analysis of flood events for the period September 1965 to December 1994 (Kahana et al. 2002) suggested that the synoptic conditions which most usually lead to flash flooding include southerly winds bringing tropical air masses associated with the tropical intrusion of the Red Sea Trough, and cyclones centred over Syria, feeding in moisture from the Mediterranean Sea. However, due to the convective nature of the resulting rainfall, it can be difficult to assess the locations most at risk from flooding and to forecast floods during rainfall events.

To investigate catchment response, one technique which has been explored is to use weather radar observations to define the characteristics of flood-generating storms (Yakir and Morin 2011). A stochastic storm transposition approach is then used in conjunction with a rainfall-runoff model to estimate the maximum floods likely to be generated in a catchment (Morin and Yakir 2012). Compared to the more usual approach of using an idealised design storm, the use of weather radar data has the advantage of providing a better representation of the influence of the spatial structure of a storm on the hydrological response.

For example, an analysis of heavy rainfall events in the Negev suggested that storm cells are typically round or elliptic, with areas of less than 100 km^2 (Dayan and Morin 2006). An ellipsoidal rain cell model was therefore used, assuming a Gaussian distribution in the core with an exponential distribution outside (Féral et al. 2003). Cell parameters were assumed to remain constant in time and storms to move with a constant speed and direction. Flows were then estimated using a semi-distributed rainfall-runoff model combining rainfall excess, hill slope and channel routing components (Bahat et al. 2009; Morin et al. 2009).

The case study selected (Yakir and Morin 2011) was for a major storm from 22 to 23 December 1993 which affected much of the Negev, including the 94 km^2 Beqa catchment. Weather radar observations from Ben-Gurion airport suggested that the catchment rainfall exceeded 70 mm resulting in a flash flood with a peak flow of 81 m^3 s^{-1} and a return period of approximately 1 in 10 years. The catchment was represented by 17 subcatchments and the storm by 56 cells, more than half of which had rainfall rates in the range 30–80 mm h^{-1}. The average cell life span was 12.6 min and the longest duration was 70 min.

The simulations suggested that the flood flows which were observed were generated by just one major cell. Sensitivity tests were then performed for this cell, assuming more than 1,000 different starting locations and different speeds and directions of travel. The resulting flow estimates were most sensitive to the assumed starting location and then to the speed and direction, with peak values of up to three-times the observed value; for example, when

(continued)

Box 12.4 (continued)

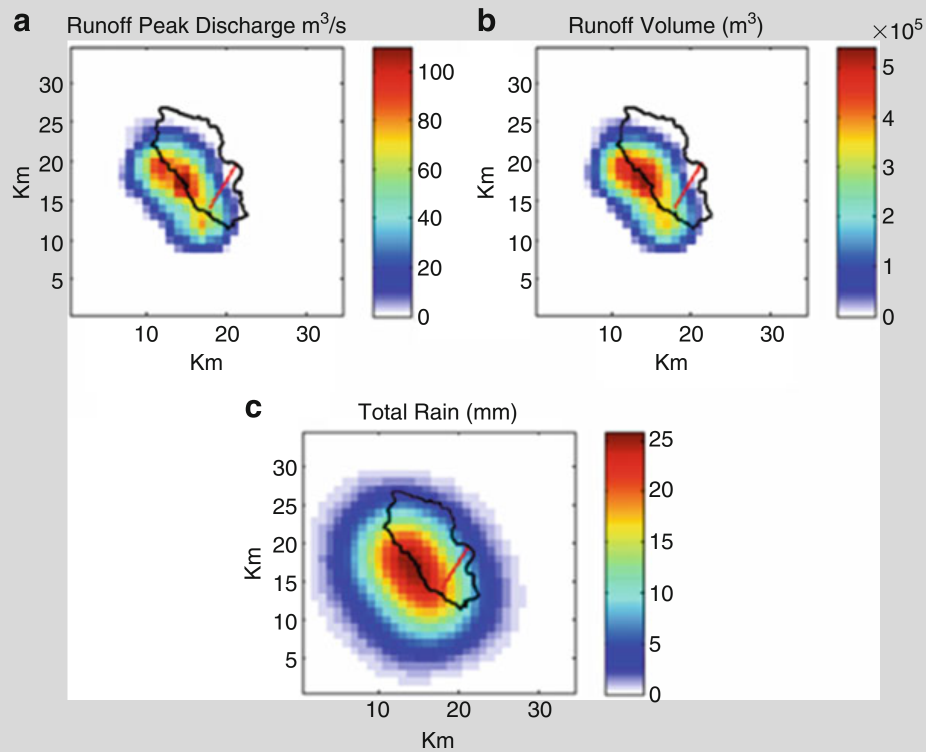

Fig. 12.8 Summary of peak flow values from the sensitivity tests on storm starting locations (**a**) the peak discharge ($m^3\ s^{-1}$) (**b**) the total runoff volume (m^3) and (**c**) the total rain over the watershed (mm). The original direction of the flooding cell over the basin (*black*) is indicated by the *red line* (Yakir and Morin 2011)

considering the starting location, the peak discharges were highest for cells originating 10–12 km from the catchment outlet as illustrated in Fig. 12.8. The maximum flow that this single rain cell can produce was assessed as 175 $m^3\ s^{-1}$ and, taking into account the rest of the rain cells, the peak discharge can reach 260 $m^3\ s^{-1}$ (Morin and Yakir 2012). A general conclusion was that the method has the potential to estimate design storms and floods of a given probability or return period.

A study in the Dead Sea area has also shown the potential for the use of weather radar data in providing flood warnings (Morin et al. 2009). In particular, the use of radar rainfall observations is likely to provide better estimates for the spatial variability in rainfall compared to telemetered raingauge networks, which are often sparse in semi-arid and arid regions. Again, the radar rainfall observations were used as inputs to a hydrological model which in this case combined a distributed infiltration component with lumped hydrological overland flow routing and transmission loss components. The model

(continued)

Box 12.4 (continued)

Fig. 12.9 A typical channel cross section in the region; the *dotted lines* show the terrace levels assumed to correspond to bankfull flow and the *solid line* shows the direction of flow (Reprinted from Morin et al. 2009 with permission from Elsevier)

was event based, operating at a timestep of 5 min, with a focus on estimating the magnitude rather than the timing of peak flows.

In a case study for the Arugot and Darga catchments, with areas of 235 and 70 km^2, flooding thresholds were derived assuming a 1 in 1.5 year return period flow, and cross-checked using a hydraulic model and recent channel survey data (e.g. Fig. 12.9). The thresholds used were precautionary values corresponding to out-of-bank flows which would merit a flood alert, although would not necessarily correspond to flooding levels.

The weather radar inputs were adjusted using a long-term bias correction based either on raingauge data or a daily adjustment. The daily adjustment scheme provided the best results for the larger catchment and similar results for the second catchment; for example, Probability of Detection (POD) and False Alarm Rate (FAR) values were in the range 0.73–0.82 and 0.23–0.25 respectively. Monte Carlo simulations, assuming a range of values for the radar bias correction and hydrological model parameters, also suggested that improved POD values could be obtained with a lower probability threshold, but at the expense of higher FAR values. Conversely, false alarm rates could be reduced by raising the threshold, but at the expense of missing some flood events. Based on these studies, an operational flash flood warning system is under development in collaboration with the Israel Meteorological Service.

Table 12.3 Some examples of probabilistic data assimilation and forecast calibration techniques

Technique	Method	Some factors to consider
Probabilistic data assimilation	Adaptive gain (e.g. Smith et al. 2012)	Simple to implement and can be applied to any type of model output
	Ensemble Kalman Filtering (e.g. Butts et al. 2005)	Requires few assumptions about the relationship between inputs and outputs, although there are potential run-time issues due to the ensemble approach
	Particle filtering (e.g. Moradkani et al. 2005)	As for ensemble Kalman Filtering but fewer prior assumptions required (although possibly more sensitive to the assumptions made)
Probabilistic forecast calibration	Bayesian uncertainty processors (e.g. Krzysztofowicz and Kelly 2000; Todini 2008; Coccia et al. 2011)	Bayesian approaches to estimate the predictive uncertainty – typically in terms of water levels – given current and previous observations and current model forecasts; for example, using model conditional and hydrological uncertainty processors
	Quantile regression (e.g. Weerts et al. 2011)	A statistical approach calibrated for predefined quantile values and lead times
	ESP post-processor (Seo et al. 2006)	A statistical approach using a combination of probability matching and regression techniques

12.4 Flood Warning

The main steps in the flood warning process are typically taking the decision to issue a warning and then disseminating that warning to the public, the emergency services and others. As noted in earlier chapters, there is often the potential to increase the warning lead time provided by making the individual steps in this process both faster and more effective.

In many organisations, this has led to improvements in a number of areas. These include the increasing use of decision support systems and new warning dissemination technologies, such as web-based and multimedia approaches, and the wider use of flood forecasting models. However, simpler organizational and procedural changes can often streamline the process: for example, through greater involvement of community representatives and by recruiting networks of observers to report on heavy rainfall and flooding incidents. Community-based flash flood warning systems are also widely used alongside regional and national flood warning services, using manual or telemetry-based observations. Social and market research studies also play a valuable role in providing a better understanding of the response of people to flood warnings in deciding how best to design warning messages and target public awareness and community education campaigns.

Chapters 1, 6 and 7 discuss many of these topics including the findings from a number of recent research studies whilst Chaps. 8–11 provide examples for specific applications. Here, two developing areas in flood warning are discussed in more detail, namely the provision of flood warnings to road users and approaches to dealing with uncertainty when issuing flood warnings.

12.4.1 Road Inundation

Several studies have shown that road users are one of the groups at greatest risk from flash flooding, particularly at night and at low water crossings. For example, as discussed in Chap. 1, a review of post-event statistics for the period 1959–2005 (excluding Hurricane Katrina) suggested that in the USA approximately 63% of flood-related fatalities occurred in vehicles, and that many of these were due to flash floods (Ashley and Ashley 2008).

Two of the main approaches to reducing the risk are public education campaigns and improved ways of warning drivers of the potential for flooding. For example, in the USA, the NOAA/National Weather Service 'Turn Around Don't Drown!' campaign produces a wide variety of educational material such as leaflets, videos, posters, and presentations (http://www.nws.noaa.gov/om/water/tadd/). This includes a set of designs for road signage to use at high risk locations such as low-water crossings and underpasses. Warnings of the risk to drivers also routinely appear in flash flood watch and warning messages from the National Weather Service and many states provide road flooding information in radio and television bulletins.

Some other options for raising awareness include adding questions on flood risk to driving licence examinations, and including leaflets describing the risks with vehicle inspection reminders. However, one challenge in targeting awareness campaigns and warning messages for drivers is often the wide variation in the way that the risk is perceived (e.g. Ruin et al. 2007). For example, one research study for two cities in Texas (Drobot et al. 2007) suggested that "people who do not take warnings seriously state that they are more likely to drive through flooded roads, as are people aged 18–35, and those that do not know that motor vehicles are involved in more than half of all flood fatalities". However a wide range of responses was received even within these two groups.

When a flood warning service is available for a specific location, then problems can be avoided to some extent by closing roads using signs or barriers, perhaps requiring a police or local authority presence. However, in flash flood situations there is often insufficient time for this type of response, which has led to the increasing use of automatic or remotely-controlled warning signs, lights and barriers. In some cases these are activated based on water levels recorded by pressure transducer sensors in road kerbs or downward-looking radar or ultrasonic gauges mounted above watercourses or areas at risk from flooding. Simpler on/off float or electrical switches provide another option and are activated when levels pass pre-defined threshold values.

With addition of a telemetry link, alerts and barrier closures can be viewed at traffic control centres (and possibly over-ridden) and text and email messages sent to operational staff. More generally, flood alerts are increasingly included in electronic variable message signs on road networks and in interrupt messages in radio bulletins. Websites are also widely used, typically showing maps of the road networks and incidents such as accidents and flooding, with links to 'live' traffic cameras. Route-specific products are also becoming available in some countries, such as for several highways in Washington State in the USA for which a website (http://i90.atmos.washington.edu/roadview/i90/) shows the route elevation profile and current conditions, webcam images and weather forecasts at key locations. Typically these types of system make use of roadside weather information systems based on solid-state rainfall, air temperature and other meteorological sensors.

Generally these approaches are most widely used in towns and cities and on major roads. By contrast, in rural areas, it is often more difficult to provide warnings due to the extent and remoteness of the areas to be covered. However, for roads running alongside large rivers, or crossing smaller streams and creeks which flood regularly, site-specific warnings are sometimes included as part of a wider flood warning service. In some cases these are supported by additional river gauges installed specifically to provide warnings for road-related flooding.

Where site-specific warnings are not possible, another approach is to identify locations at risk from past experience; in some cases supported by regional flood risk modelling studies. Actions such as on-site inspections and road closures can then be targeted at the highest risk areas. Rainfall depth-duration alarms or a Flash Flood Guidance approach are also widely used to provide early warning of potential flooding problems (see Chap. 8). In some forecast centres, the threshold levels for high risk low water crossings and roads traversing floodplains are surveyed in order to improve the accuracy of these alerts.

In recent years, the use of distributed rainfall-runoff modelling approaches has also been considered as a way of helping to provide warnings to road users at vulnerable locations (Versini et al. 2010). For example, in parts of southern France, locations which are potentially at risk are identified from a Digital Terrain Model, considering river crossings, low water accumulation points, and road sections adjacent to watercourses. In tests of a prototype, the model was configured for approximately 2,000 locations at a grid resolution of 1 km^2 and using 15 min rainfall estimates (Naulin et al. 2011).

12.4.2 Dealing with Uncertainty

When a flash flood develops, the situation often changes rapidly with many conflicting sources of information. Emergency response and civil protection staff therefore need to take decisions based on a wide range of factors, of which flood warnings and forecasts are just one aspect (e.g. Morss and Ralph 2007; Baumgart et al. 2008).

Some approaches to managing this complexity include having well-defined and rehearsed procedures in place, and decision support and other tools to help to maintain situational awareness (see Chaps. 6 and 7). This increasingly includes formalizing procedures for sharing on-site information provided by staff and trained volunteers; for example via a flood incident response website.

These issues generally relate to the emergency response, which typically involves a wide range of people with different skills, priorities, concerns, sources of information and time constraints. The procedures used also differ widely between countries and organisations. For example, Sorenson and Mileti (1987) identified the following four main types of uncertainties faced by emergency managers: interpretation (recognition of event), communications (physical ability to communicate), perceived impacts of decision (causing adverse responses), and exogeneous influences (time availability). Here the entries in brackets are the items which were documented most frequently. However, for flood incident response, although there has been some limited research on the influence of uncertainty on the decision-making process, there have been few practical applications. For example, some techniques which have been proposed for real-time use or emergency planning include fuzzy set logic, linguistic reasoning, Bayesian Networks, artificial neural networks and agent-based modelling, as well as simpler risk-based assessments (e.g. Environment Agency 2007; Simonovic and Ahmad 2005).

Within the overall flood warning process, the development of approaches to dealing with uncertainty is perhaps most advanced for flood forecasts and the need to advise users of the uncertainty in forecasts is widely recognized (e.g. Krzysztofowicz 2001; UN/ISDR 2006; Schaake et al. 2007). For flash floods, this is a particular consideration since the use of rainfall forecasts is often a key step towards extending the warning lead times provided, and meteorological services increasingly provide rainfall forecasts in ensemble form (see Chap. 4). Weather radar and multi-sensor precipitation products are also increasingly accompanied by quality indices or ensemble estimates of uncertainty (see Chap. 2).

A key question then is how to make best use of this information and how this is likely to affect the roles and responsibilities of those involved. For example, one potential advantage of probabilistic forecasts (Krzysztofowicz 2001) is that "…. they decouple the task of forecasting, which ought to involve solely the principles of science, from the task of decision-making, which should involve the decision maker's evaluation of consequences of alternative actions and possible events". Collier et al. (2005) also note that "We need to keep a clear distinction between the needs of hydro-meteorological services and flood emergency operations. In the former case the interest is in getting the best possible forecast, whereas in the latter case the interest is in making the best possible decision."

Whilst the value of a probabilistic approach is increasingly recognised within forecasting agencies, an important consideration is how best to communicate this information both to operational staff and end users, including civil protection organisations and the public. This is a developing area in flood forecasting (e.g. Demeritt et al. 2010, 2012; Ramos et al. 2010), although much can be learned from research in related fields, such as weather forecasting and hurricane evacuation (e.g. National Research Council 2006). It is also worth noting that, as in weather forecasting (World Meteorological Organisation 2008b), there are usually additional less quantifiable sources of uncertainties once a forecast has been generated; for example, arising from a forecaster's interpretation of model outputs, simplification and encapsulation of those conclusions into warning messages and then – perhaps most importantly – interpretation of those messages by end users.

Another consideration is that there are sometimes wide variations in the technical background of users, although an important point is that "over time, and with sufficient experience and user education, it is possible to improve the level of user understanding and sophistication" (World Meteorological Organisation 2008b). Thus, for probabilistic flood forecasting applications, as in meteorological forecasting the demand for information on uncertainty is likely to increase both from organisations (e.g. emergency responders, local authorities, critical infrastructure operators) and the public.

As discussed in Chaps. 5–11 and Sect. 12.3, a number of flood forecasting services have already made major steps along this path, with an increasing number of operational and pre-operational systems in place (e.g. Cloke and Pappenberger 2009). Some approaches which are used to present and interpret forecasts include:

- Cost-loss approaches – methods which compare the costs (C) of taking action with the potential losses (L) if no action is taken, assuming consistent application of the same strategy across a number of events (no hedging)
- Probabilistic thresholds – decision criteria which include a probabilistic component; for example issuing a warning if 60% or more of ensemble members for a given lead time exceed a pre-defined threshold
- Visualisation – map-based and graphical outputs such as spaghetti diagrams, box and whisker plots, plumes, confidence limits, and 'postage stamp' maps

For example, in cost-loss approaches, at the simplest level a consideration of the total cost across a number of events (e.g. Katz and Murphy 1997) shows that the minimum expenditure occurs if action is taken every time that a probability threshold equal to C/L is exceeded. However there are many complicating factors to consider in a full analysis, as discussed later in this section.

For visualization approaches, there are many options for presenting results to highlight the spatial, temporal and site-specific aspects of the situation, and these are best developed in consultation with end users. In meteorological forecasting, some widely used approaches include monitoring of the clustering of ensembles (e.g. Fig. 12.10) and the use of 'postage-stamp' formats in which multiple maps are presented on a single page or screen showing all current scenarios. For flood forecasting, options such as plumes, spaghetti diagrams (e.g. Fig. 12.7) and confidence intervals are widely used. Also checks for the consistency (or otherwise) between successive forecasts often provide clues regarding the nature of an event (convective, synoptic scale etc.) (e.g. Pappenberger et al. 2011a, b). Tabulations of the persistence in threshold exceedances between forecast runs are also useful in the interpretation of outputs (e.g. Bartholmes et al. 2009).

When probabilistic thresholds are used, some methods used to define thresholds include past experience (e.g. trial and error, forecast verification) and cost loss approaches. Another option is to use a relative economic value approach, based on the additional benefits obtained compared to a climatological forecast, relative to those which would result from a 'perfect' forecast (e.g. Richardson 2012).

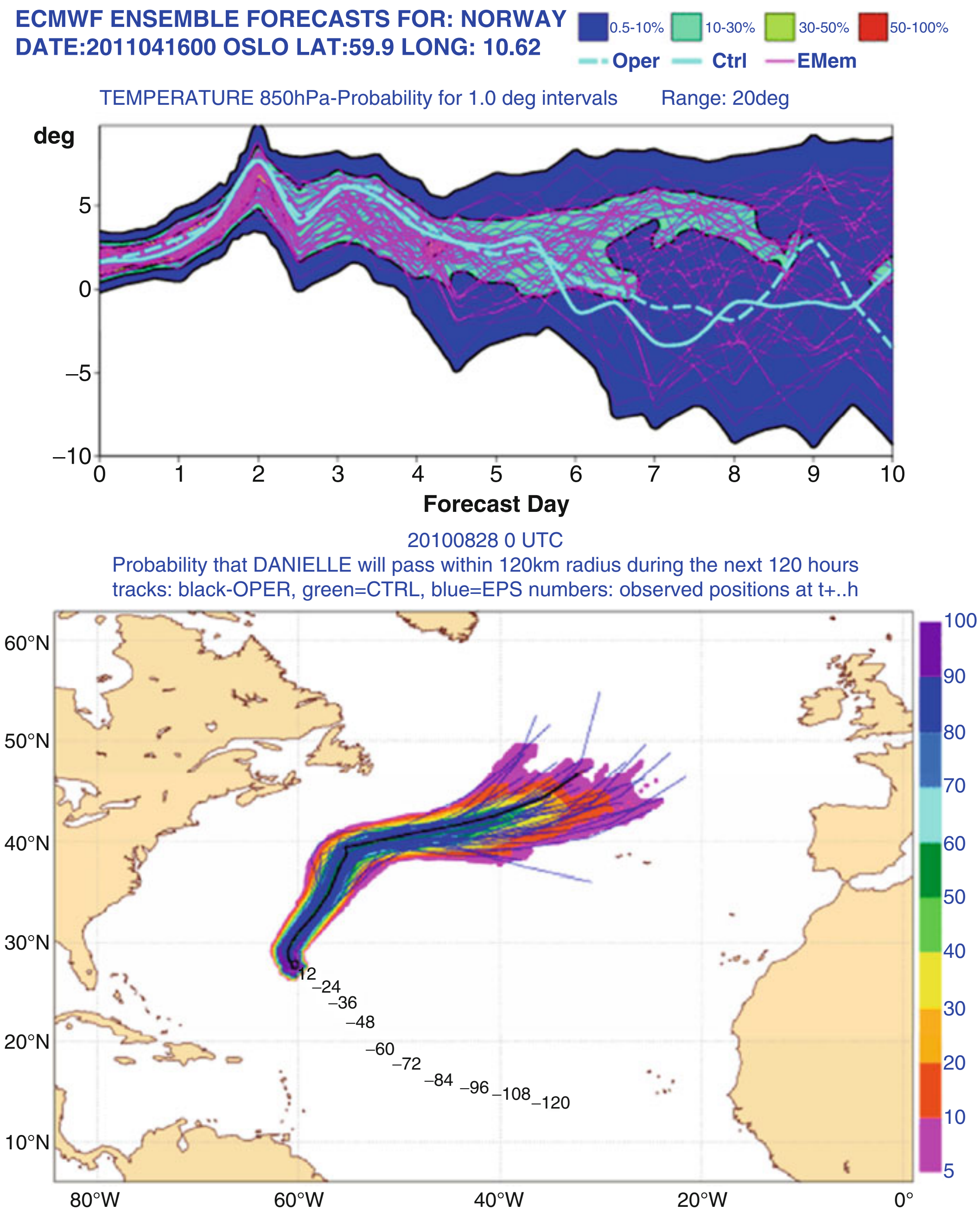

Fig. 12.10 Examples of the visualization of ensemble meteorological forecasts, showing a plume diagram for the 850 ha air temperature forecast for Oslo on 16 April 2011 at 00:00 UTC and a 5-day ahead strike probability map for tropical storm Danielle for 28 August 2010 at 00:00 UTC. In the plume diagram, the ensemble forecast indicates a bi-modal development between days 5 and 7, whereas the operational forecast and the Control follow one branch (Persson 2011; source ECMWF)

For many of these approaches, quantitative estimates of uncertainty are required so forecasts should normally be improved using probabilistic forecast calibration or data assimilation techniques (see Sect. 12.3). For example, a local authority might choose to temporarily close access to a riverside path at a lower probability threshold than, say, that used in deciding to order evacuation of a residential area. In the first case, the costs of taking action are small, but are significantly higher in the second case, although with different potential losses and risk profiles for each situation.

Other factors are sometimes included in these types of analyses; the aim being to better understand how people (including forecasters) actually respond in practice, which often departs from the simplest forms of model (e.g. Morss et al. 2010). Some examples include attitudes to risk (risk taking, risk neutral, risk averse etc.), tolerance to false alarms, and how both the optimum response and losses vary with lead time and flood severity (e.g. Roulston and Smith 2004; Roulin 2007; Martina and Todini 2009). These approaches also provide one possible route to estimating the incremental economic benefits gained from a probabilistic approach compared to a deterministic approach (e.g. Verkade and Werner 2011). More generally, the use of Bayesian techniques has been proposed to provide an overall framework within which to consider topics such as forecast performance, flood warning thresholds and end user requirements (e.g. Krzysztofowicz et al. 1994).

These are developing areas but show potential for situations where there are actions which have a clearly identifiable cost or benefit which can be expressed in financial terms. A corresponding loss or societal impact also needs to be specified if the action is not performed and flooding occurs. Ideally, costs and losses need to be defined as a joint exercise between model developers and potential end users, particularly where the losses are more than just financial (e.g. loss of life, reputational). In that case, non-dimensional utility functions are widely used, typically expressing scores on an arbitrary scale (typically 0–1).

For example these types of approaches have been used in a number of operational reservoir and polder management systems, balancing the needs for flood control with hydropower and other applications (e.g. Bowles et al. 2004; Todini 2005; Georgakakos et al. 2007; Kok et al. 2010; Addor et al. 2011). Another potential application is for situations where river control structures are operated regularly, such as tidal barriers and flood detention areas, where the costs (or losses) from interruptions to navigation or farming (for example) can be compared with the benefits from flood mitigation.

Another consideration is that ideally information would be available for a wide range of past events when calibrating and evaluating the chosen approach. Typically this requires a long-term archive of both observations and forecasts, derived from a reforecasting or hindcasting exercise using both models and instrumental records which are representative of the current operational situation (see Chaps. 4 and 5). For more extreme events there is also the issue that sometimes there may be few if any suitable calibration events even within a hindcast period. Also some of the underlying assumptions about how people behave may no longer apply, such as when faced with a catastrophic or life-threatening situation (e.g. Haimes 2009).

These are all interesting areas for research, and in operational use one area which is proving particularly useful is to provide long lead time warnings based on ensemble outputs. For example, Chap. 8 provides several examples of low cost or low impact actions which can be taken at long lead times, based on rainfall alarms. These include activating flood response plans, updating staff rosters, placing temporary restrictions on access to roads and other areas potentially at risk, issuing flood watches, and various flood mitigation measures. In particular, for safety or staffing reasons, some activities are more easily performed during daylight or normal working hours, whilst others require significant time to complete, such as installing demountable defences.

A probabilistic or ensemble approach also potentially opens the route to a more risk-based approach to issuing flood warnings, taking account of both the probability and consequences of flooding. Tailor-made warnings could then be issued to individual users, or groups of users, via multimedia, cell phone and other individually targeted warning dissemination systems. For example, this approach is already being used in some meteorological services, such as in Finland where users are provided with a range of options for the thresholds at which they would like to receive heavy rainfall alerts by mobile phone (see Chap. 4).

However, the extent to which probabilistic information is made available varies between organisations. In addition, as in meteorological applications, some users may lack internet or smartphone access to view some of the more sophisticated types of outputs (e.g. National Research Council 2006; World Meteorological Organisation 2008b). Some key issues to consider therefore include the user requirements for information, message design, dissemination technologies, and training and awareness-raising campaigns.

However, at the other extreme, some users may wish to receive the raw ensemble outputs from forecasting models for post-processing and inclusion in their own decision support systems, such as hydropower, tidal barrier and reservoir operators. Also, since end users are often best placed to assess the consequences of flooding, this usually requires more of a collaborative approach between those who issue warnings and the recipients of warnings. In particular, for a flood warning service, this could mean moving more towards the role of providing information upon which others take the decision to act.

As for any new technique, the introduction of probabilistic techniques into the flood warning process therefore requires consideration of the implications throughout the monitoring, forecasting, and warning chain. As is often the case, this requires a multidisciplinary approach involving forecasting experts, social scientists and – most important of all – the communities, emergency response and civil protection organisations that make use of flood warnings.

12.5 Summary

- Research needs for flash flood warning systems extend across the whole monitoring, forecasting and warning process. However, it can sometimes take several years for research ideas to translate into practice due to the need to avoid risks to the operational service. Hydrometeorological testbeds provide one way to accelerate that process by allowing new approaches to be evaluated in a pre-operational setting. The use of open source software and common measurement, modelling and data exchange standards also facilitates this process.
- For precipitation monitoring, a general requirement is to improve the spatial resolution and accuracy of observations, and to routinely provide end users with estimates for the uncertainty. For flash flooding applications, some techniques

which show potential include phased array weather radars, the use of microwave communications links, and adaptive sensing approaches. Ongoing research with X-band radars is also yielding operationally useful results. For the future the Global Precipitation Mission has the potential for a step change in the usefulness of satellite precipitation estimates in flash flood applications.

- Research in techniques for monitoring catchment conditions generally tends to consist of incremental improvements to existing approaches. However new approaches continue to be developed and some recent examples which are relevant to flash flood applications include low-cost wireless sensor networks and particle image velocimetry techniques.
- Improvements in rainfall forecasting are potentially a benefit for many applications and this is consequently a major and well-funded area for research. For flash flood applications, some current areas of interest include the development of high resolution storm scale and convective scale models – and associated data assimilation, forecast verification and post-processing techniques – and of seamless products for all lead times with associated estimates for uncertainty. During high impact events, some meteorological services also envisage a more interactive role for forecasters to maximize use of their expertise in the process; for example by initiating ensemble forecast runs and targeting adaptive observations towards the areas of most rapid development.
- In the area of flood forecasting, the use of ensemble rainfall forecasts is starting to become routine although still with many issues to resolve regarding the probabilistic content of outputs. The development of probabilistic data assimilation and forecast calibration techniques is another active area for research, with the overall aim to provide reliable estimates of the uncertainty from all sources. More generally, many aspects of hydrological research are potentially of benefit in flash flood forecasting applications with two topics of particular interest being flood estimation and warning in arid regions and data assimilation for real-time distributed and hydrodynamic models.
- For the dissemination of flash flood warnings, new opportunities continue to arise from the ever expanding range of communications technologies available and a better understanding of the social responses to flooding. Some current areas of interest include the provision of warnings to road users and how best to use probabilistic observations and forecasts within the flood warning process. In particular, as with many other innovations in flash flood warning, the implications for using probabilistic outputs need to be considered throughout the monitoring, forecasting and warning chain, including the socioeconomic aspects.

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Glossary

Action Table a table of actions to take as meteorological, river and/or coastal conditions exceed predefined threshold values

Antecedent Conditions the state of wetness of a catchment prior to an event or period of simulation (Beven 2012)

Automatic Weather Station (AWS) an instrument for automatically measuring meteorological information in real-time including (typically) wind speed and direction, solar radiation, air temperature, humidity, and rainfall, and possibly other parameters, such as soil temperature and snow depth

Basin see *Catchment*

Boundary Conditions constraints and values of variables required to run a model for a particular flow domain and time period *(continued)* (Beven 2012)

Business Continuity Management a management process to identify and manage the hazards or threats which can disrupt the smooth running of an organization or delivery of a service

Calibration adjustment of the parameters of a model, either on the basis of physical considerations or by mathematical optimization, so that the agreement between the observed data and estimated output of the model is as good as possible (see *Model Calibration* in UNESCO/WMO 2012)

Catchment drainage area of a stream, river or lake, or area having a common outlet for its surface runoff (see *Basin or Catchment* in UNESCO/WMO 2012)

Climatology the description and scientific study of climate in all its aspects. Often the term is used to refer to the observed distribution of a meteorological parameter, or set of parameters, over a number of years (typically a 30-year period) (Troccoli et al. 2008)

Conceptual Hydrological Model simplified mathematical representation of some or all of the processes in the hydrological cycle by a set of hydrological concepts expressed in mathematical notations and linked together in a time and space sequence corresponding to that occurring in nature (UNESCO/WMO 2012)

Contingency Table a table summarizing the relationship between the frequencies of occurrence of two or more variables, at the simplest level consisting of a 2×2 matrix

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Cost Benefit Analysis a decision-making technique which compares the likely costs of an action or investment with the expected benefits

Cost Loss an analysis technique which compares the cost of taking an action with the likely losses if that action is not taken

Data Assimilation the use of current and recent real-time observations of meteorological and catchment conditions to update a forecast

Data Collection Platform automatic measuring device with a radio transmitter to provide contact via a satellite with a reception station (UNESCO/WMO 2012)

Debris Flow see Chap. 9 for a range of definitions

Decision Support System Decision Support Systems are a general type of computerized information system that supports business and organizational decision-making activities (NASA 2009)

Deterministic Model a model that, with a set of initial and boundary conditions, has only one possible outcome or prediction (Beven 2012)

Dissemination in emergency response, notification of warnings by a range of direct, community-based and indirect methods

Distributed Model a model that predicts values of state variables varying in space (and normally time) (Beven 2012)

Downscaling the translation of a forecast from one spatial and/or temporal resolution to a finer resolution. In spatial downscaling, the term is frequently applied to the translation of a forecast from a gridded average to a local point (Troccoli et al. 2008)

Drainage Basin see *Catchment*

Ensemble Forecast a number of realisations of future meteorological, river or coastal conditions based on alternative values for initial conditions, boundary conditions, model parameter values, and other sources of uncertainty, which reflect the inherent uncertainties in observations and models

Evapotranspiration quantity of water transferred from the soil to the atmosphere by evaporation and plant transpiration (UNESCO/WMO 2012)

False Alarm a warning which is issued but for which no subsequent event occurs

Flash Flood see Chap. 1 for a range of definitions

Flash Flood Guidance "…the average rain needed over an area during a specified period of time to initiate flooding on small streams in an area" (Sweeney 1992).

Flood Defence see Levee

Flood Fighting emergency response actions to reduce or prevent flooding, including reinforcing levees, sandbagging, and installing demountable defences

Flow Routing a technique used to compute the movement and change of shape of a flood wave moving through a river reach or a reservoir (UNESCO/WMO 2012)

Forecasting Point a location at which it is useful to have a forecast of future flow conditions

Geographic Information System (GIS) computer software for the presentation and analysis of spatial datasets

Glacial Lake Outburst Flood a flood caused by the sudden release of water from a lake formed by moraine, ice or similar

Hurricane see *Tropical Cyclone*

Hydrodynamic Model a solution to the equations expressing mass, momentum and energy conservation of water, sediment, heat and other parameters in a river, estuary or coastal reach

Hydrograph graph showing the variation in time of some hydrological data such as stage, discharge, velocity, sediment load etc. (UNESCO/WMO 2012)

Ice Jam accumulation of ice at a given location which, in a river, restricts the flow of water (UNESCO/WMO 2012)

Initial Conditions values of storage or pressure variables required to initialize a model at the start of a simulation period (Beven 2012)

Intangible Losses losses which cannot easily be expressed in economic terms

Levee water-retaining earthwork used to confine streamflow within a specified area along the stream or to prevent flooding due to waves or tides (UNESCO/WMO 2012). Alternative names include flood defence and dike.

Mesoscale pertaining to atmospheric phenomena having horizontal scales ranging from a few to several hundred kilometers, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones, and topographically generated weather systems such as mountain waves and sea and land breezes (AMS 2012)

Multi-Criteria Analysis (MCA) a structured decision-making technique widely used for evaluating alternative options

Nowcast a meteorological forecasting technique based on extrapolation of current conditions, typically observed by weather radar or satellite

Numerical Weather Prediction (NWP) a meteorological forecasting technique which obtains approximate solutions to the mass, momentum and energy conservation equations for the atmosphere, including transfer processes at the land and ocean surfaces

Orographic Precipitation precipitation caused by the ascent of moist air over orographic barriers (UNESCO/WMO 2012)

Parameter a constant that must be defined before running a simulation (Beven 2012)

Polder a mostly low-lying area artificially protected from surrounding water and within which the water table can be controlled (UNESCO/WMO 2012)

Quantitative Precipitation Estimate (QPE) an estimate for current precipitation which is typically based on weather radar or satellite observations. When outputs are combined and other sources included, this is often called a Multi-sensor Precipitation Estimate

Quantitative Precipitation Forecast (QPF) a forecast of rainfall and other types of precipitation, typically based on nowcasting or Numerical Weather Prediction techniques

Rainfall-Runoff Model a model which converts observed or forecast rainfall into estimated river flows

Rating Curve see *Stage-Discharge relationship*

Real-Time Updating see *Data Assimilation*

Resilience the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase its capacity for learning from past disasters for better future protection and to improve risk reduction measures (UN/ISDR 2004)

River Gauging Station a location where observations of water level and discharge are made

Situation Report a brief report that is published and updated periodically during a relief effort and which outlines the details of the emergency, the needs generated and the responses undertaken by all donors as they become known (IDNDR 1992)

Snow Pillow a device filled with antifreeze solution and fitted with a pressure sensor which indicates the water equivalent of the snow cover (UNESCO/WMO 2012)

Stage-Discharge Relationship or Stage-Discharge Relation – relation between stage and discharge at a river cross section and which may be expressed as a curve, table or equation(s) (UNESCO/WMO 2012)

Threshold pre-defined values for meteorological or catchment conditions which are used to initiate or escalate warnings or take emergency response actions. Sometimes called triggers, criteria, warning levels, alert levels or alarms

Tropical Cyclone a synoptic-scale to mesoscale low pressure system which derives its energy primarily from evaporation from the sea in the presence of high winds and low surface pressure and condensation in convective clouds concentrated near its center (Holland 2012). The term tropical cyclone is used in the Indian Ocean, hurricane in the Atlantic and Eastern Pacific Oceans, and typhoon in the Western Pacific

Typhoon see *Tropical Cyclone*

Ungauged Catchment a catchment or subcatchment in which flows are not recorded to the extent required for the application

Vulnerability the conditions determined by physical, social, economic, political and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UN/ISDR 2004)

Watershed see *Catchment*

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