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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This book has benefited from discussions with many people. Following some time working in fluid mechanics, I moved to the Centre for Ecology and Hydrology in Wallingford in the UK. There, I had the opportunity to work on a wide range of research and consultancy projects, with much of this work overseas. Subsequently, as part of a large engineering consultancy, my focus turned to real-time applications, including areas such as probabilistic forecasting and flood warning.

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

Part I Techniques

Part II Applications

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)

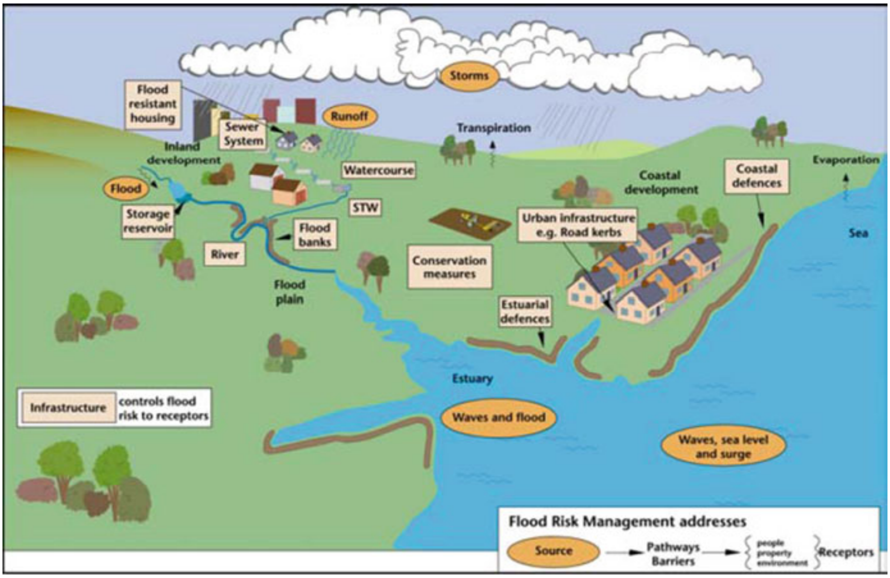

Fig. 1.1 A hydraulic perspective of the physical flooding system (Office of Science and Technology 2003)

- 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

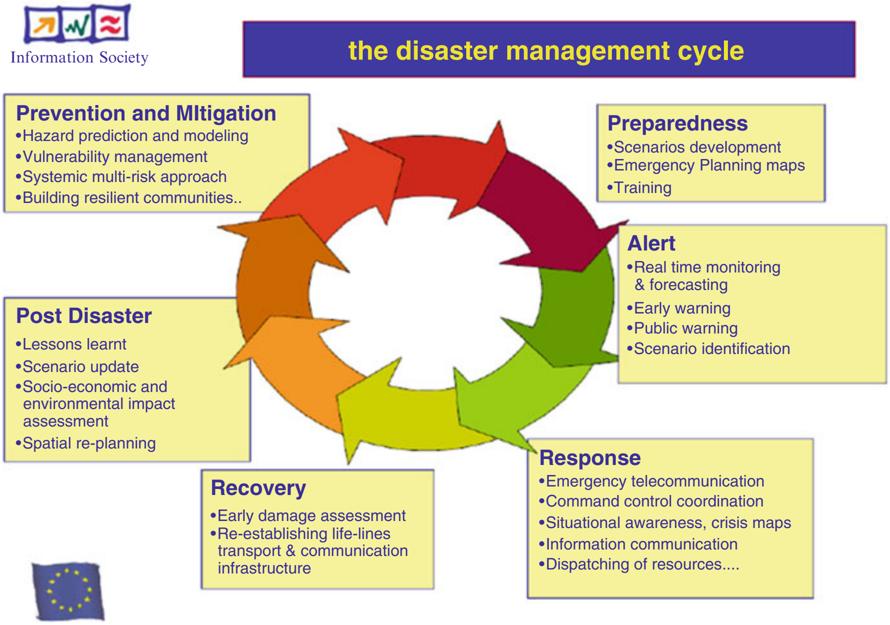

Fig. 1.2 The Disaster Management Cycle (© European Union, Information and Communication Technologies 2006; CORDIS, http://cordis.europa.eu/)

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.

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