A Review of Current Knowledge

Floods: alleviation, protection, response and risk management

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This review is one of a series of Reviews Of Current Knowledge (ROCKs) produced by FWR. They focus on topics related to water supply, wastewater disposal and water environments, which may be the subject of debate and inquiry. The objective of each review is to produce concise, independent scientific and technical information on the subject to facilitate a wider understanding of the issues involved and to promote informed opinion about them.

Review of Current Knowledge

Floods: alleviation, protection, response and risk management

Flooding at Dorchester-on-Thames

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Executive Summary

Flooding is the most widespread of all natural hazards, often arising from adverse meteorological conditions such as:

- intense or prolonged rainfall in river catchments
- storm surges at the coast and in estuaries
- storm-generated waves at the coast.

Flooding may be triggered by a series of other natural hazards. For example, earthquakes may cause tsunamis. They also cause landslides which may block river valleys and impound water. These landslide deposits later breach resulting in flooding downstream. Another source of flooding is the failure of water management infrastructure such as dams and raised flood protection embankments.

In many countries, little of the coastline or land area has escaped human influence, with increasing pressures over generations from settlement, agriculture, industry and commerce. The human influences include water and flood management activities which control the extent and frequency of floods and the drainage of water from the land. Our perception of floods and how to react to them has changed over time. Originally, floods were regarded as acts of God and society accepted the vagaries of nature. With technological development in the 18th, 19th and 20th centuries the concept developed of man attempting to overcome or control nature, an approach or attitude which continued until very recently. During this period the dominant philosophy was one of taming floods, flood defence and flood prevention. Today, with the emergence of sustainability as a dominant driver of international policy and human activity, there is a move towards social responsibility and the development of general policies for flood risk management.

Flood risk management can be viewed as a continuing cycle of activities with prevention and protection at the fore in normal times. When a flood is imminent or in progress, the attention moves to flood warning and emergency management responses. After the flood there is a period of recovery, relief and review to learn lessons before the next flood occurs. Flood risk management recognises that the reduction of flood damage needs active engagement with the public at large so that when a flood comes, individuals and businesses are prepared and can act appropriately. This approach aims to create greater resilience within communities.

Flood risk can be analysed through a systematic consideration of:

- the sources of the floodwater
- the pathways by which the water moves over the land surface
- the exposure of people, property, businesses and the environment to the floodwaters
- the consequences of inundation on everything exposed to the floodwater.

Flood risk management is achieved through a portfolio of measures including the construction of traditional flood protection schemes, the use of policies to restrict inappropriate development on floodplains, the installation of flood warning systems and the testing of action plans to protect the population.

Internationally, policies and practice in flood risk management are evolving in response to many drivers including:

- consideration of potential climatic changes in terms of precipitation and sea levels
- increasing potential for damage to the growing world infrastructure
- decreasing acceptance of flooding by communities
- competing demands on public expenditure
- ageing of existing flood defence infrastructure.

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1 Introduction

Flooding is an important issue because it can cause serious and costly damage to infrastructure, property, possessions, agricultural crops, etc. Major floods affect lives and livelihoods, particularly in developing countries where flood risks may be high and flood management procedures are not well developed.

The situation regarding flooding is not static. The increasing world population and the trend towards urbanisation in flood prone areas exacerbate the effects of flood events. There are also growing worries that climate change may affect the frequency and magnitude of floods in some areas.

Flood defence measures have been used over centuries as a means of combating floods. These may comprise the construction of flood banks in rivers and sea walls on the coast, designed to protect towns, villages, agricultural land, etc. Alternatives have been to enlarge river channels, by deepening or widening or both, to provide more flow capacity or to store floodwaters for later release at a more acceptable flow rate.

Some of the methods used historically to alleviate flooding have been shown to be unsustainable in the sense that natural processes, of sediment movement for example, have undermined the immediate gains achieved by the works. Furthermore, many of the earlier methods paid but lip service to environmental issues.

Flooding is a natural process which has some benefits, particularly to agricultural land. Complete protection against flooding is therefore neither practical nor desirable. The challenge today is to use flood alleviation methods which limit damage and are both sustainable and environmentally benign.

Natural Disasters

The United Nations International Strategy for Disaster Reduction (UNISDR 2009) defines a disaster as "*A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources.*"

The United Nations has assessed that of the 2,200 water related disasters catalogued between 1990 and 2001, 50 per cent related to floods. Outbreaks of water-borne disease, droughts, landslide events and famine made up the other 50 per cent. Floods accounted for 15 per cent of all deaths related to natural disasters, famines 42 per cent. Developing countries accounted for 20 per cent of the total number of disasters and over 50 per cent of all fatalities. The geographical breakdown of natural disasters during this period was:

- Africa: 29 per cent
- Asia: 35 per cent
- The Americas: 20 per cent
- Europe: 13 per cent
- Oceania: 3 per cent.

The Munich-Re re-insurance company has compiled information on the economic effects of natural catastrophes for many years, providing an annual summary through their NatCatSERVICE. Figure 1 illustrates the costs, and trends with time, of natural catastrophes for six decades. Clearly the losses in any particular year are very variable according to the number and type of catastrophes that occur, with major contributions from specific events such as the Indian Ocean tsunami in 2004 and the devastation of New Orleans by hurricane Katrina in 2005. It is also evident that the proportion of losses that are insured is also variable, with insurance being more prevalent in developed economies.

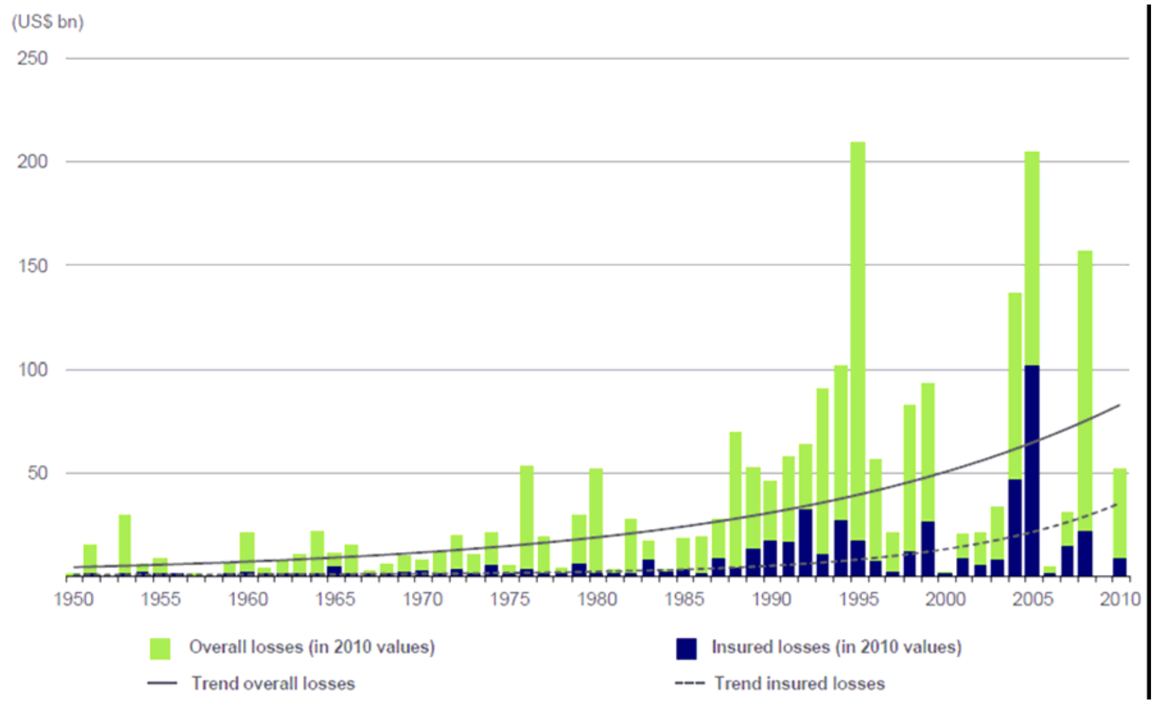

Figure 1 Overall and insured losses - trend for natural catastrophes worldwide 1950 to 2010[1]

As an example of costs to the UK economy, the independent review of the summer 2007 flood, (Pitt 2008), comments that "*To put the events into context, there were over 200 major floods worldwide during 2007, affecting 180 million people. The human cost was more than 8,000 deaths and over 40 billion pounds worth of damage. But even against that dramatic back-drop, the floods that devastated England ranked as the most expensive in the world in 2007.*"

The Pitt report assesses the total insured cost of the 2007 floods in the UK as over three billion pounds. The NatCatSERVICE information on the most damaging floods between 1980 and 2010 ranks this flood as the second most costly for insured losses in the period and indicates that 75 per cent of the total loss was insured. This is in contrast to the 2002 flood of the River Elbe in the Czech Republic and Germany which was the most costly but where the insured losses were only about 20 per cent of the 16.5 billion dollars total.

The increasing world population and the likely effects of climate change suggest that flooding could become an even more serious issue in the future.

Historic Floods

Data on flood flows is notoriously difficult to obtain. Quite apart from the technical issues of measuring flood flows during the event or estimating flood flows retrospectively, the main emphasis during and immediately after flood events is to minimise loss of life and to support flood victims in their rehabilitation process.

One initiative to document flood flows has been established by the International Association of Hydrological Sciences (IAHS) which aims to contribute to the UNESCO International Hydrological Programme (IHP) and to the Hydrology and Water Resources Programme of the World Meteorological Organisation (WMO). The latest report, (Herschy 2003), on this project updated the earlier 1984 edition. For the 2003 edition IAHS sought information from 170 countries on large historic floods. Some countries did not respond whilst the returns from others were variable in quality

[1] © 2011 Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE – As at January 2011

and coverage. Forty eight countries provided new information which was added to the data provided in 1984 by 102 additional countries.

So what are the maximum flows which have been observed from catchments of a particular size? Francou and Rodier collected data on historic floods and published the worldwide data shown in Figure 2 (Francou & Rodier 1967). The data included a range of catchment sizes from 12km^2 to 4,640,000km^2. Geographically the data came from the following countries: Australia, Brazil, China, Cuba, French Polynesia, Iceland, India, Japan, Madagascar, Mexico, Nepal, New Caledonia, New Zealand, North Korea, Pakistan, Philippines, Puerto Rico, Russia, South Korea, Tahiti and USA.

Additional data for maximum recorded floods is provided in Figure 2 for European rivers. Countries included are Austria, Croatia, Denmark, France, Germany, Hungary, Netherlands, Romania, Slovakia, Spain and UK. The UK data is for maximum floods observed on the Thames at Teddington (1894, 1,064m^3/s, 9,670km^2), the Severn at Bewdley (1947, 671m^3/s, 4,325km^2), the Lyn at Lynmouth (1952, 511m^3/s, 102km^2) and the Valency at Boscastle (2004, 160m^3/s, 20km^2).

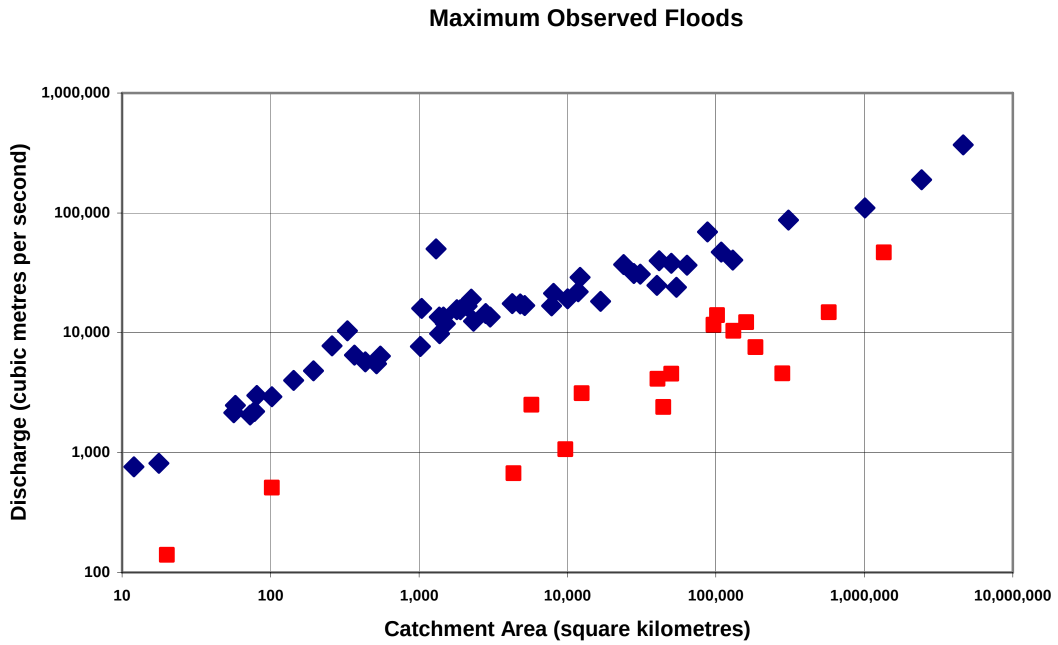

Figure 2 Maximum Observed Floods (source Francou & Rodier 1967)

It is evident that the European maximum floods are substantially less, for the same sized catchment, than the worldwide maxima. This is likely to be attributable to the more benign European climate. For example, in the UK, the maximum precipitation in the past for all durations is only about 25 per cent of the worldwide maxima (Wilson 1990).

Illustrations of floods

Figure 3 Dhaka, Bangladesh

Flooding in the streets of Dhaka, the capital city of Bangladesh, are commonplace during the spring and summer months when the rivers Ganges, Jamuna and Meghna are subject to high flows mainly from Himalayan snowmelt.

Figure 4 Jhelum River, Pakistan

The rivers Jhelum and Indus both drain the Himalayas in the northern areas of Pakistan. They are subject to major seasonal floods in the spring and summer months.

Figure 5 Exeter, UK

Extensive damage occurred in Exeter in 1960 when the river Exe inundated low-lying areas of the town. The flood was caused by heavy rainfall over the Devon/Somerset catchment area. A flood protection scheme was subsequently built which has, to date, performed successfully.

Figure 6 Severn Valley, UK

The valley of the river Severn is particularly vulnerable to flooding, usually resulting from heavy rainfall over the upper catchment. These pictures are from the 1990 flood which was a 1 in 20 year event.

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Content of ROCK

This ROCK is concerned with flood mitigation and the inextricable links to river basin management. It indicates current thinking on flooding problems and how alleviation of these problems should be tackled.

The main factors which need to be considered regarding flooding include technical, social and governmental aspects as follows:

Technical:

- flood forecasting technologies
- flood warning procedures and responsibilities
- flood protection including consideration of structural and non-structural methods
- procedures for evaluating the overall monetary value of proposed flood alleviation works
- design methods which are based on a sound analysis of risk.

Social:

- the importance of understanding the issues, including acknowledgement that absolute security from flooding is neither technically possible (or even desirable) nor economically justifiable
- the importance of good communications before, during and after flood events.

Governmental:

- the creation of sustainable conditions for future generations
- the consideration of environmental implications of flood defences in the broadest sense
- the establishment of appropriate institutional arrangements and policies for flood management
- the facilitation of integrated planning over river basins.

The ROCK aims to provide a concise description of these factors on a worldwide basis but with a more specific European and UK focus.

2 Aspects of Flooding

This chapter covers several of the broader aspects associated with flooding.

The observation, measurement and categorisation of floods involve science which has developed mainly in the last two centuries. Instrumentation includes devices for measuring water levels, water velocities and flows and the data is processed using a range of techniques from simple desktop analyses to complex computer simulations.

Floods can be categorised into different types depending upon location. Small catchments, particularly in hilly or mountainous regions, can generate intense floods during short heavy rainfall events. Large catchments, particularly in tropical and monsoon areas, can generate widespread flooding which can last for weeks or even months. In coastal areas flooding is caused by waves, tides and tidal surges. The inundation takes place over periods measured in hours but the flood waters often drain away over much longer periods.

The physical processes which contribute to flooding are to be found in meteorological, hydrological and hydraulic sciences. These processes all contribute to the magnitude of flood events in particular locations at particular times.

There are also societal dimensions associated with flooding. Human activities, such as urbanisation, can affect the risk of flooding and conversely flooding can have adverse consequences which affect the lives and livelihood of people.

One further aspect of flooding is the question of compensation for the victims of flooding. Should this be covered by insurance and, if so, how should risks be assessed in advance? Or is this a centralised issue for local authorities and/or governments?

Finally in this chapter we discuss the development of the approach to flooding problems. Historically floods were regarded as acts of God and ad-hoc solutions were developed, after flood events, to protect particular communities against similar occurrences in the future. Today the approach is more sophisticated and can be described as flood risk management. This approach looks more strategically at flood risks and the value of any proposed flood alleviation measures in terms of the costs and the benefits. Environmental and societal costs and benefits are beginning to be taken into account although it is often difficult to assign monetary values to these.

Observation and measurement of flood events

The question is often asked "What is the probability of a flood of a certain magnitude occurring at a particular location in any one year?" To answer this question with any degree of certainty demands that a considerable amount of local data is collected over an extended period of time and that these data are subjected to rigorous statistical analyses and modelling.

There are at least five characteristics which are useful in comparing one flood with another. These are:
- the peak water level observed during the flood event
- the date and time at which the peak level occurred
- the peak discharge during the flood event
- the duration of the flood and the shape of the flood hydrograph
- the flooded area.

The peak water level

It may be thought that the observation of the peak water level during a flood would be a straightforward process. However, during major flood events, the emphasis has to be on saving lives and infrastructure, not on the observation of the details of the water movement. Occasionally there are automatic water level gauges which have enough range to observe and log the peak water level unattended. However, this is a rarity. More often than not the determination of the peak water level is carried out after the flood event and is based on observations of wrack marks on trees, buildings, bridges etc. The accuracy of these observations is not always good since some may have been influenced by surface waves, the artificially high or low elevation of water against a fixed object or subsidence which has taken place after the event.

Figure 7 Wrack marks remaining in a field two weeks after the Boscastle flood of 2004

The date and time

This is perhaps the easiest of the five parameters to establish. Certainly the date on which the peak occurs should be known and in many cases this is adequate for the subsequent statistical analysis of flood frequencies. The time of the peak may be important in small, steep catchments.

The peak discharge

In the case of modest floods, for example for those where the river remains within bank, it is relatively straightforward to determine the peak flow. There may be an established flow gauging station nearby at which the peak flow can be read from the known stage-discharge relationship at the site. If this is not the case, relatively simple hydraulic calculations can provide the discharge from a knowledge of the cross-sectional area of the channel, the slope of the channel and the estimated roughness of the wetted perimeter.

Where over-bank flow occurs during flood events the calculations are still manageable but there is an extra element of uncertainty due to the interactions between the flow in the river and the flow over the adjacent flood plain. The calculations are only valid for relatively straight channels with flood plains of near-uniform width.

During major flood events, straightforward calculation techniques become untenable and other more sophisticated approaches are called for. In recent years 2-D and 3-D numerical models have been developed and these are able to simulate more complex geometries. The models are valuable tools with which to retrospectively simulate and quantify observed flood events, including the establishment of peak discharges.

Recently, the European research projects FLOODsite and HYDRATE have produced a systematic means of post-event survey for estimating the maximum discharge for flash floods, which pose particular difficulties (Gaume & Borga 2008). The Environment Agency commissioned the Conveyance Estimation System (CES) to reduce the uncertainty in flood assessments. The software produced for CES contains a photographic catalogue of river vegetation and associated roughness estimates, together with a computational procedure to estimate the rating curve from the cross-section geometry (McGahey et al. 2008).

The duration and shape of the flood hydrograph

The duration and shape of the flood hydrograph may vary from location to location and also from event to event. For example, a flood downstream of a confluence of two or more rivers may have two or more peaks if each of the tributaries contributes at different times. Again, numerical modelling after the event may be used to simulate the complex situation and throw light on the magnitude of the sources of the floodwaters.

The flooded area

The extent of the flooded area is important because it defines the area subject to damage and disruption. Data on flooded areas has historically been gathered either from visual observations taken at ground level or from aerial photography.

A recent development has been the use of satellite imagery combined with powerful computerised database systems to store and display data in a readily digestible form. This technique has great potential and is currently the subject of major research investigations to determine what data might be presented and in what form. A good example is the research by the Dartmouth Flood Observatory which was founded in 1993 at Dartmouth College, Hanover, USA. It moved to the University of Colorado in 2010. The work uses satellite imagery acquired by NASA, the Japanese Space Agency and the European Space Agency and the basic presentation is spatial flood mapping on a global scale. However, beneath this basic layer of information there is more detail such as flood hydrographs at specific locations, river flow statistics, etc.

The Dartmouth Flood Observatory project is relatively young, covering only the last 18 years or so. Hence it has only limited value in highlighting long-term trends. However, as a method of acquiring large quantities of flood data and presenting the data in a user-friendly way it has great potential. Readers are encouraged to visit the Dartmouth Flood Observatory web-site: http://floodobservatory.colorado.edu/index.html.

Physical processes

Precipitation

Precipitation varies with time and location. It is recorded using many different techniques from simple mechanical land based rain gauges which are read manually, to sophisticated remote sensing devices which use ground or satellite based radar techniques.

It is not easy to obtain widespread and accurate data on precipitation. Raingauge networks are commonly dense in populated areas but sparse in rural areas and rare in the upper reaches of many river basins. There is also a significant cost in collecting precipitation data and this causes differences in the quality and quantity of data between developed and developing countries.

The UN Food and Agricultural Organisation (FAO) maintains the AQUASTAT database of water related topics which is available on-line at http://www.fao.org/nr/water/aquastat/main/index.stm. The FAO relies on member countries for information. The worldwide data obtained is not always consistent, nor is it presented in a uniform format. In particular, countries change their names and/or boundaries and the definition of which countries to group within particular regions has not been entirely consistent over the years.

This ROCK uses the eight regions identified by FAO, namely:

- Asia
- Europe
- Middle East and North Africa
- Sub-Saharan Africa
- North America
- Central America and Caribbean
- South America
- Oceania.

Table 1 summarises average precipitation per annum across the world.

Table 1 Average precipitation per annum (mm)

Region	Precipitation (mm)	Wettest countries	Precipitation (mm)	Driest countries	Precipitation (mm)
Asia	1,080	Malaysia	2,880	Turkmenistan	160
		Indonesia	2,700	Uzbekistan	210
		Bangladesh	2,670	Mongolia	240
		Singapore	2,500	Kazakhstan	250
		Philippines	2,380	Azerbaijan	450
Europe	550	Iceland	1,940	Moldovia	450
		Switzerland	1,540	Russia	460
		Albania	1,490	Finland	540
		Poland	1,410	Ukraine	570
		United Kingdom	1,220	Hungary	590
Middle East and North Africa	310	Lebanon	660	Egypt	50
		Turkey	590	Libya	55
		Israel	440	Saudi Arabia	60
		Morocco	350	United Arab Emirates	80
		Afghanistan	330	Algeria	90
Sub-Saharan Africa	1,240	Sierra Leone	2,530	Mauritania	90
		Liberia	2,390	Niger	150
		Equatorial Guinea	2,160	Mali	280
		Gabon	1,830	Somalia	280
		Congo	1,650	Namibia	290
North America	610	United States	720	Canada	540
Central America	1,320	Costa Rica	2,930	Mexico	750
		Panama	2,690	Cuba	1,340

Region	Precipitation (mm)	Wettest countries	Precipitation (mm)	Driest countries	Precipitation (mm)
and Caribbean		Nicaragua	2,390	Dominican Republic	1,410
		Trinidad and Tobago	2,200	Haiti	1,440
		Jamaica	2,050	Belize	1,710
South America	1,760	Colombia	2,610	Argentina	590
		Guyana	2,390	Paraguay	1,130
		Suriname	2,330	Bolivia	1,150
		Ecuador	2,090	Uruguay	1,270
		Venezuela	1,880	Chile	1,520
Oceana	2,210	Papua New Guinea	3,140	Australia	530
		Solomon Islands	3,030	New Zealand	1,730
WORLD	960	Papua New Guinea	3,140	Egypt	50

Runoff

Runoff is a term used to describe surface flows which are sourced by precipitation. Runoff may be an immediate consequence of a rainfall event or may occur much later as snowmelt, the latter being common in regions with major seasonal variations in temperature.

The relationships between precipitation and runoff are complex and are affected by many factors including:

- the nature of the precipitation, rain or snow
- the intensity and duration of the precipitation
- whether the storm generating the precipitation is static or whether it is moving and, if so, in which direction
- the topographical nature of the catchment on which runoff is occurring
- the geological conditions within the catchment
- the antecedent ground conditions, wet, dry, frozen, etc.

Research in recent years has provided a reasonable framework which enables runoff to be predicted at specific locations during and following precipitation events. In the UK the former Institute of Hydrology (IH), now part of the Centre for Ecology and Hydrology (CEH), has developed procedures related mainly to UK conditions. The initial Flood Studies Report (FSR) was published in 1975 (NERC 1975) and this was updated by the Flood Estimation Handbook (FEH) following the acquisition of more comprehensive data on high intensity short period storms (IH 2000). Work continues and a supplementary report is now available for download which improves and makes more transparent the original FSR/FEH procedures (Kjeldsen 2007). Other methods derived by the international community are included in Beven's primer on rainfall-runoff modelling (Beven 2001). Chapter 3 discusses hydrological flood estimation, probability and frequency at greater length.

The actual runoff intensity depends on a number of factors including geographical location and the size, the nature and the condition of the catchment. An indication of the effect of catchment size, for example, can be gained by looking at observed maximum floods and comparing the discharge with the size of the contributing catchment. Figure 8 shows the same data plotted in Figure 2 but in this revised format. The discharge per unit area of catchment clearly falls with increasing catchment size. Again, European rivers show modest floods compared with world maxima.

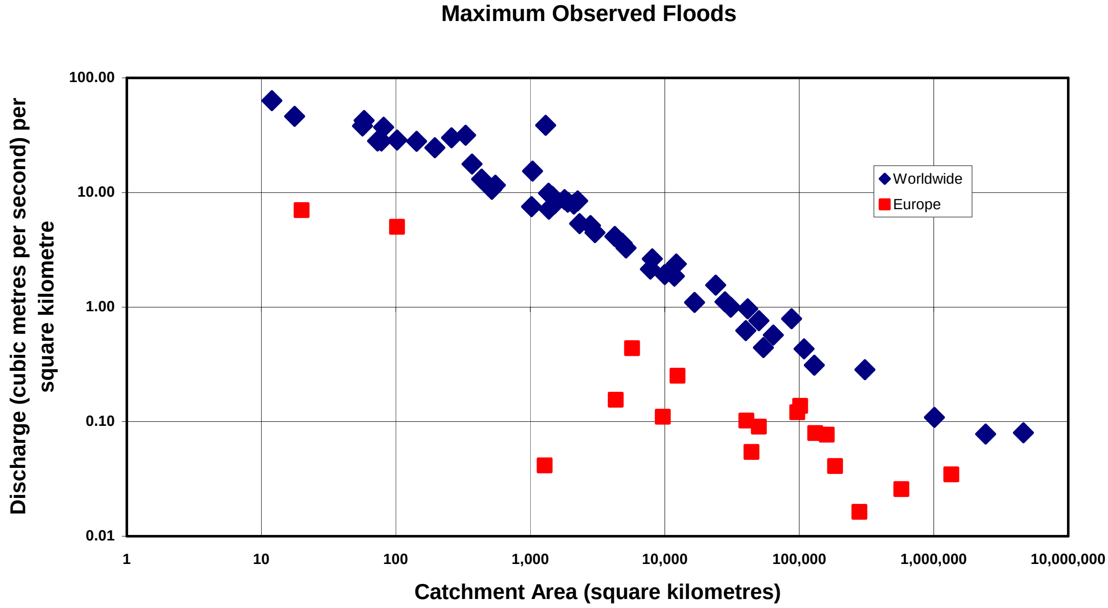

Figure 8 **Maximum observed floods in terms of catchment size (source Francou & Rodier 1967)**

Floods in smaller catchments are predominantly caused by high intensity rainfall events and the magnitude of the flood can be influenced by the direction in which the storm passes over the catchment.

In larger catchments floods mainly result from long duration rainfall events or from seasonal snowmelt in mountainous areas. Figure 9 shows an example from the river Indus in Pakistan at the location of Tarbela reservoir.

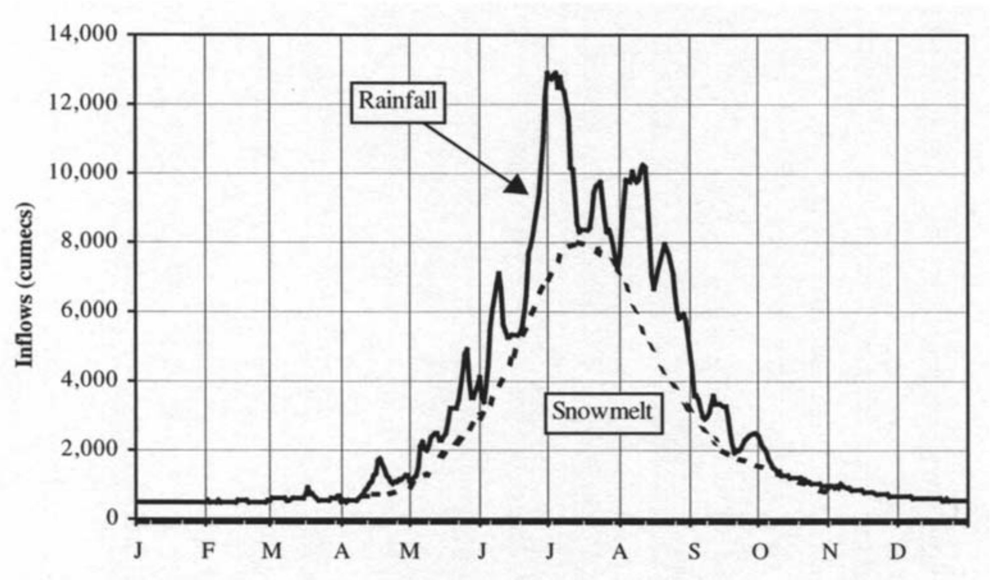

Figure 9 **Annual average flow in the Indus river (source HR Wallingford)**

Most of the catchment upstream of Tarbela is within the mountainous Himalayan region and includes seven out of the ten highest mountains in the world. The Indus therefore is subject to snowmelt floods in the spring and summer months. The lower part of the catchment is in a monsoon region and flooding can arise from major and prolonged rainfall events as happened in 2010. Figure 9 shows the annual average contribution to the runoff made by rainfall and snowmelt. In this case the monsoon rainfall contributes about ten percent of the total runoff.

Flood Propagation

Methods for the reliable prediction of how floods propagate through a catchment have developed mainly in the last 50 years. These methods for analysing the movement of water both above and below ground level are today more scientifically secure. But also rainfall and stream flow data have become more comprehensive and provide good evidence for validating the new predictive techniques.

A flood hydrograph changes in character as the storm water moves from the upper reaches of the catchment to the lower river reaches. In the case of a simple single thread channel the magnitude and timing of the peak flow varies with the distance travelled. Assuming no lateral inflows, flows disperse and translate along the channel so that peak flows diminish with distance but the high flow period lasts longer. In the case of more complex river networks additional flows are generated by tributaries and the prediction of downstream conditions becomes more complex. However, it remains important to estimate the hydrograph at any location during a rainfall or flood event in order to know in advance the probable extent of flooding.

There are three main tools for predicting the propagation of floods:

Analytical solutions

Analytical solutions make simplifying assumptions about the detailed topography and the hydraulic laws governing the movement of water. Analytical solutions are easy and quick to use and have a role in early assessments of flooding problems.

Physical models

Physical models cover the area of interest at a reduced linear scale. Physical models represent the detailed topography and infrastructure in a realistic manner but can suffer from scale effects which relate to the viscous and surface tension properties of water. Physical models are used less and less for flood propagation issues but are still useful for looking at detailed flow conditions in complex situations e.g. urban areas. They can be used retrospectively to assess flows from observed levels during major flood events or in the development of physical solutions to flooding problems.

Computational models

Computational models cover a range of complexity from steady flow in a channel, through 1D network models to comprehensive 3D models of local areas which demand high powered computing facilities and extensive data. Computational models are extensively used for a range of applications from single river reaches to whole river basins. Current UK and European practice is for the widespread use of 2D computational models for risk mapping of flood extents using digital terrain models based upon remotely sensed data at a spatial resolution of 10m or finer. Computational models are also coupled to real time meteorological and hydrological data for short term flood forecasting.

All three tools have their place in solving flooding problems but the emphasis moves inextricably towards the use of computational computer models, facilitated as they are by ever increasing computer processing speed and storage, coupled with improvements in the background science and the availability of more comprehensive data. The books edited by Knight and Shamseldin (Knight & Shamseldin 2006) and written by Novak, Guinot, Jeffrey and Reeve (Novak et al. 2010) provide in-depth coverage of flood processes and modelling approaches.

Impacts on society

Floods and other major hazards are part of nature. They have always existed and will continue into the future. Mankind, in its search for social and economic development, has interfered with these natural processes by developing the infrastructure which we see in the world today. Very little of the coastline or land area has escaped human influence with increasing pressures over many generations. Examples include towns and cities which have been built in areas which would otherwise provide flood paths and flood storage. Agricultural developments on floodplains are now commonplace and provide food for an ever increasing population.

Flood risk

The historic approach to the reduction of flood risk was to engineer flood defences, divert flows and enlarge channels, etc. In the case of fluvial floods these works were designed to contain historic floods within specific flow paths. Coastal defence works were designed to protect against historic storm conditions. The limitations of such an approach have been recognised with new policies being implemented, for example, through the European Directive on the assessment and management of flood risks, see Chapter 5. Improvements in the approach to flooding problems now include:

- a more rational approach to the design conditions in terms of the probability of occurrence
- a move towards a more strategic consideration of the whole river basin in the case of fluvial flooding
- a shift from defensive action against flood hazards towards the management of flood risks in a broader sense
- a desire to reverse some of the unfortunate consequences of previous flood protection measures by restoring natural flood zones
- an acknowledgment that mitigation and non-structural measures are potentially more efficient and sustainable methods of approaching flooding problems
- the development of works and procedures to minimise the risk of damage to infrastructure and loss of life within areas of high flood risk.

Many of these new approaches have an influence on social issues such as local and strategic planning. It is also clear that the new approaches demand a much greater understanding of flooding issues by the general public in order that the strategic aims might be met and that individuals are aware of their own exposure to flooding risks.

Floods emergencies

The Centre for Research on the Epidemiology of Disasters (CRED) at the Université Catholique de Louvain has assembled the EM-DAT database (http://www.emdat.be/) of all natural disasters from 1900 until present. The CRED summary data on floods is divided between continents and shows a geographic diversity of impact, with the greatest incidence of floods and fatalities per event being in Asia whilst the lowest are in Oceania and Europe. Worldwide, the average annual number of fatalities recorded in the CRED database from 1980 to 2010 is around 7,000 lives from river flooding alone. This figure excludes cyclones, hurricanes, storm surges, tsunami etc. Deaths are mainly caused by direct drowning during floods, particularly in flash floods, but there is often consequential loss of life due to water related epidemics or, in some cases, famine.

One important aspect of recent research into flooding problems has been the development of ideas to minimise the adverse effects of specific flood events. There are two main aspects:

- how to warn people of impending flooding
- how to prepare people in order that they take appropriate action during flood events.

These issues are discussed further in Chapter 6.

Environmental impacts

The principle of sustainable development has received international acceptance and commitment as a fundamental policy aim for national governments and supra-national institutions, particularly since the 1992 Earth Summit at Rio (UNCED 1993). The classic definition of sustainability was formulated in the Bruntland report (Bruntland 1987) as development which " *…meets the needs of the present without compromising the ability of future generations to meet their own needs.*"

However, the working out of this principle in practice presents considerable challenges in that the impacts of development have to be assessed in a holistic manner with long time-horizons. In terms of river basin management, at its broadest scale, it may encompass:

- scenarios for social, legal and political institutions
- spatial planning of land use, agriculture and industry
- scenarios for the future climate and associated impacts and adaptations
- scenarios for future demography, resource demands, trade, societal expectations etc.

For sustainable development to be a viable concept the management of flood plains must be technically, economically, socially and politically achievable. It requires a broad view of the interventions in the river catchment area rather than local single-issue considerations.

Can we reverse some of the less well conceived, or outdated interventions we have previously made to our environment? Is it possible to put the clock back? Do we want to put the clock back?

River restoration has become a topic of interest in some, mainly developed, countries because such projects can form part of a sustainable development plan for the river basin. The objectives of river restoration are normally to create a wider diversity of eco-systems and improve biodiversity, by bringing the river into a closer contact with its flood plain (Bettess & Fisher 1998). The visual amenity of the watercourse may be improved and its natural function for flood storage and conveyance regained.

The objectives of restoration are, in part, to recreate particular habitats and ecotopes and these need to be defined with their consequent physical characteristics. From this a design for the restoration can be developed by collaboration between ecologists, geomorphologists and hydrologists. The linkage between hydrodynamic and ecological assessments, "eco-hydraulics", was identified as a research need at the first EU RIBAMOD workshop on river basin modelling (Cunge & Samuels 1996). It has been a strong research theme since then, driven in Europe and the US by environmental legislation such as the European Water Framework Directive and the European Floods Directive.

Although restoration of rivers may be desirable in terms of the encouragement of biodiversity, such interventions may be contentious to some riparian landowners if it has an adverse impact on their use of the land. Hence public participation in the decisions on whether, and how, to restore a river is needed to ensure that the actions are socially acceptable and thus sustainable.

A new approach to flood risk management

Extensive research has been supported by the European Commission in the last 10 years into river basin and flood risk management. In 2002 the Water Directors of the European Union agreed to undertake an initiative on flood prediction, prevention and mitigation. The initiative produced a best practice document (EC 2003) which updated the earlier United Nations and Economic Commission for Europe (UN/ECE) guidelines on sustainable flood prevention (UNECE 2000). A summary of the best practice principles and approaches are given, with minor editing, below:

<u>Basic principles and approaches for sustainable flood prevention, protection and mitigation</u>

(a) As far as possible, human interference into the processes of nature should be reversed, compensated for and, in the future, prevented. It is necessary to promote and harmonise changes in water policies and land-use practices, as well as environmental protection and nature conservation, in order to improve flood management in the framework of integrated river basin management.

(b) This should cover the entire catchment area of watercourses and promote the co-ordinated development, management and conservation of actions regarding water, land and related resources. Such a holistic approach is based on multilateral and even multinational co-operation, including inter-disciplinary planning for the whole catchment area.

(c) Considering the evolution and trends, the approach to natural hazards requires a change of paradigm. One must shift from defensive action against hazards to management of the risk and living with floods.

(d) Human uses of floodplains should be adapted to the existing hazards. Appropriate administrative processes and measures should be developed to reduce the risk of flood damages.

(e) Mitigation and non-structural measures tend to be potentially more efficient and in the long-term more sustainable solutions to water-related problems and should be enhanced, in particular, to reduce the vulnerability of human beings and goods exposed to flood risk.

(f) Nevertheless, structural defence measures will remain important elements and should primarily focus on the protection of human health and safety and valuable goods and property. Requirements of nature conservation and landscape management should also be taken into account.

(g) The major part of the population and infrastructure is located in large urban areas so efforts for avoiding flood problems should be focused on these urban areas. River overflows are not the only cause of urban floods. They can also be caused by high rainfall intensities over the built up areas combined with inappropriate sewer systems. Special attention should be paid to the drainage of rainwater through the sewer systems in our cities.

(h) Everyone who may suffer from the consequences of flood events should also take, if possible, his/her own precautions. To this end, appropriate information and forecasting systems should be established by the competent authority.

(i) Mutual understanding is essential. One should not pass on water management problems from one region to another. The appropriate strategy consists of a three-step approach:
- retain rainfall at the spot where possible
- store excess water locally
- discharge water to the receiving watercourse at an acceptable rate.

Flood alleviation should also be based on the precautionary principle.

(j) In flood-prone areas, preventive measures should be taken to reduce possible adverse effects of floods on aquatic and terrestrial ecosystems such as water and soil pollution.

Implementation

To implement the basic principles and approaches, co-operation at all government levels, co-ordination of sectorial policies regarding environmental protection, physical planning, agriculture, transport and urban development is needed. As regards trans-boundary waters, cooperation is required among the riparian countries to harmonise national policies and strategies, and to draw up concerted action plans.

Pre-requisites for action

(a) Knowledge is required of potential threats. Flood alleviation should not be limited to flood events, which occur often. It should also include rare events, as they pose the greatest risk to human safety.

(b) There is a need for reliable information to enable the necessary precautions to be taken.

(c) There is a need for interdisciplinary co-operation regarding all phases of risk assessment, risk management, mitigation planning and implementation of measures.

(d) The answer to the question “Which level of flood protection can we accept?" presumes that one has examined what could happen, i.e. that the risks have been properly assessed.

3 Flood frequency, flood probability and flood estimation

The estimation of the probability of floods occurring at some time in the future or over a certain period is a fundamental component of understanding and analysing flood risk. Estimates of future probability are often made by analysing the nature and frequency of historic floods.

There are two means of expressing the frequency or probability of a flood which are in common use in practice. These are the “return period” (symbol T) and the “annual probability” of occurrence (symbol P). For annual maximum floods, the annual probability and return period are related by T = 1/P.

Return period is the average expected (mean) time in years between floods exceeding a particular threshold. Return period is traditionally used to express the frequency of occurrence of an event, although it is often misunderstood as being a probability of occurrence, or as implying a degree of regularity in the re-occurrence of the conditions.

Probability is a measure of the chance that an event will occur in the future and can be expressed as a fraction, a percentage or a decimal. For example, the probability of obtaining a six with a shake of a fair dice is 1/6, 16.7 per cent or 0.167. Flood probability is often expressed with reference to a time period, for example, the annual flood exceedance probability, which relates to the random chance of this occurrence in any one year.

Since major floods are uncommon, random events, it is likely that at any one site there will be few if any observations of extreme flood flows, velocities or levels. Several specialised statistical methods have been developed to estimate flood frequency from records at the site of interest possibly in combination with information at other analogous sites. There are four broad categories of method for estimating flood probability at a site, for a catchment or for part of a catchment:

- statistical analysis of local records
- index flood estimation
- event-based hydrological modelling, usually using design rainfall events
- continuous flow simulation of runoff processes.

These methods all contain a degree of uncertainty and may lead to different estimates for a flood of any particular probability. In fact it is often an over simplification to label an actual historic flood, or some hypothetical design case, as having a single value of probability, since the maximum flood discharge may have one probability and the overall flood volume a higher or lower value. This is of more than just theoretical interest since flood defence infrastructure will need different hydrological design characteristics. The sizing of flood storage reservoirs should be based upon the statistics of flood volume. However, the spillway arrangements will require sizing based upon the peak flood discharge for a catastrophic flood, often the "probable maximum flood". The height of flood defence embankments will depend primarily on the peak flood discharge and not the flood volume.

Statistical analysis

For a statistical analysis of flood frequency and probability, the main steps required are:

- selection of the appropriate statistic
- selection of the frequency distribution for the statistic
- fitting the parameters of the frequency distribution to the available data.

Selection of statistic

The selection of the statistic for assessment of flood frequency and probability depends upon the use of the end information. This issue is of particular importance where the decision criteria include loss assessment for damage which has seasonal variability and depends upon the duration of the event rather than just the maximum intensity. Statistics should be collected through choosing the start and end of the hydrological year so that the flood season does not span adjacent years. The data, which may be extracted from the flow records for analysis include:

- annual maximum (AM) discharge for instantaneous flood peaks. The AM series is also known as the "annual flood series" (AFS).
- peak-over-threshold (POT) instantaneous flood peak discharges which exceed a specified threshold of flow. The POT series is also known as the "partial duration series" (PDS).
- mean flow or volume for specified durations, 1 day, 3 days, 10 days, 1 month, etc.
- annual maximum water level (stage)
- AM or POT rainfall depth for a specific duration e.g. 15 mins, 1 hour, 12 hours, 1 day, 5 days, etc.

The difference between the AM and POT data is in the number of events which are recorded for analysis in any water year, with the POT statistic extracting more values from the observations. The AM series records a single event in each year, whereas a POT data set typically records three peaks in a year but in very dry years may record none. The events in an AM series can reasonably be assumed to be statistically independent of each other, whereas other selection criteria may be needed to assure no serial dependence in a POT series. Where there are several potential sources of flooding, a joint probability assessment of the interaction of these sources may be needed. For example the joint occurrence of a surge tide and high river discharge in an estuary may be required (Samuels & Burt 2003). In such cases, AM data is not appropriate if the data needs to be analysed for correlation between different flood sources. In these cases a full time history is required.

Selection of distribution

There are several statistical distributions for the estimation of the probability of extreme floods from data at a particular site. There is no clear-cut, single best choice of statistical distribution. The choice will depend upon the hydrometeorology of the area and also national or professional guidance. Moreover, the appropriate statistical distributions will differ for AM and POT data, but the frequencies assessed from both types of data set should converge for extreme (rare) flood events. Two examples of national approach are given below.

UK practice

Between 1975 and 2000, the Flood Studies Report (NERC 1975) defined the UK practice. Through theoretical considerations of the behaviour of the frequency of annual maximum floods, the Flood Studies Report recommended the generalised extreme value (GEV) family of distributions (GEV-1, GEV-2 and GEV-3). The GEV-1 or "Gumbel" distribution has two parameters which are fitted to site values of the first and second moments of the data, it has a fixed value of the third moment known as the skewness. The GEV-2 and GEV-3 distributions allow for different values of skewness to be represented giving a broader range of theoretical behaviour of the frequency associated with extreme floods. The use of the GEV distribution was carried forward into the world flood study (Meigh & Farquharson 1985; Meigh 1995).

UK flood estimation practice now follows the procedures of the Flood Estimation Handbook (FEH) (IH 2000). The handbook identifies several distributions, generalised logistic, extreme value, log Pearson and log normal. For analysis of AM flow records there is now a national preference for the use of the generalised logistic distribution. The choice of this distribution is made from an assessment of its ability to fit a wide range of flood data series.

US practice

The US Department of Agriculture (USDA) has identified several possible distributions for US practice in the appropriate part of the National Engineering Handbook (USDA-NRCS 2000). These are the normal, Pearson III, two-parameter gamma, extreme value and binomial distributions. Whereas the FSR and FEH provided specific recommendations on frequency distributions to be used in the UK, there is no single recommendation for US practice. Instead there is a discussion of the merits of the distributions and pragmatic guidance is given on how best to use them. However, the National

Engineering Handbook comments that the national weather service and certain federal, state, local and private organizations have publications based on extreme value theory.

Fitting the distribution to the data

The final stage in statistical estimation is to develop the parameters for the distribution from the data available. A frequency of occurrence is associated with each observation and then the best distribution is determined by estimating the statistical moments of the data. There are several choices needed in determining the plotting position for observations in an annual maximum series. There are statistical arguments that the best plotting rule is linked to the distribution (Meigh 1995). Meigh recommends that the Gringorten rule should be used for the GEV distribution. However, the US practice (USDA-NRCS 2000) is to use the Weibull plotting rule to associate a frequency assessment to ranked observations using the log Pearson III or log-normal distribution. UK practice is to use standard software for the FEH methodology to undertake the fitting of distribution parameters, whereas the US National Engineering Handbook (USDA-NRCS 2000) illustrates how this may be achieved through tabulation and recommends investigating any unusual events, or outliers, as identified on a graphical plot of the fitted distribution and data before the result is finalised.

Index flood estimation

Index flood methods provide a means of estimating extreme floods from regionalisation which integrates information from a number of gauges within a catchment or in hydrologically similar catchments to provide a greater body of data for analysis. The approach was outlined by (Darlrymple 1960), and the method provides the conceptual basis of the regional flood estimation in many countries. The method has two fundamental steps:

- a homogeneous region is identified where a common probability model of floods can be reasonably assumed to apply, taking account of climatology and catchment characteristics. The probability model is standardised through using multiples of an index flood and is sometimes called the "growth curve".
- an index flood estimator is needed at the particular river site concerned. This may be calculated from observations at the site or, in the absence of local data, this will be derived from characteristics of the catchment hydrometeorology.

There has been much effort devoted to the development of the regionalised flood growth curves for the first of these steps for national and international use. One example is the world flood study (Meigh & Farquharson 1985; Meigh 1995).

The European funded research project, FRAMEWORK, addressed methods for the estimation of the index flood (Bocchiola et al. 2003). Bocchiola et al. provide a framework for estimation of the index flood in five different cases:

- river sites with a flow gauging station
- river sites lying in a gauged catchment
- river sites located in an ungauged basin which is located in a hydrologically homogeneous region
- river sites close to an impounding structure, eg a dam, which alters the natural flow series
- river sites located at historical sites in urbanised ungauged basins.

For each of these cases Bocchiola et al. present one or more methods of index flood assessment, depending upon the data available. The methods to obtain the index flood are:

- analysis of the AM series
- analysis of a POT series
- use of scale invariance
- estimation from historical flood marks
- fluvial morphological assessment of bank-full discharge
- derived distribution using the modified “geomorpho-climatic” method

- hydrological simulation based on rainfall-runoff modelling with observed or hypothetical rainfall characteristics.

Index flood methods are the basis of one of the approaches in UK hydrological design practice. They provide the statistical approach for the procedures given in both the current Flood Estimation Handbook (IH 2000) and the former Flood Studies Report (NERC 1975). Software based on these procedures have promoted their widespread national implementation in the UK and Ireland. The practice uses the general logistic distribution, which has three parameters, in the index flood method. It defines a growth curve with all floods normalised by the site value of the "median" flood (QMED). Data is drawn from other hydrologically similar sites into a "pooling" group for the analysis. The need for, and size of, the pooling group depends upon the maximum return period that is required from the analysis. Unacceptable uncertainties may occur if the data sets are too short. The QMED value may be estimated from the annual maximum series if there are sufficient years of record, say 14 or more. Alternatively it may be estimated from an analysis of the POT data series using 2 to 13 years of data through a weighted average of selected peaks (IH 2000). Where there are under 2 years of data, the FEH procedures require catchment characteristics to define QMED. This method is specific to the UK.

Event-based hydrological modelling

The Unit Hydrograph (UH) method is commonly used for the estimation of the design flood from rainfall. The UH method has underpinned hydrological design for generations and is in widespread current use internationally, two examples are the SCS method from the USDA (USDA-NRCS 1972; USDA-NRCS 2004; USDA-NRCS 2007) and the revitalised FEH method in the UK (Kjeldsen 2007). This design procedure is used to estimate flows at a specific point of interest in a catchment. The UH is the hypothetical response of the catchment to a unit depth of rainfall, e.g. 10mm, spread uniformly over a specified time period, e.g. 1 hour. UK practice is to use a triangular shape for the unit hydrograph with a faster rate of rise than recession from the hydrograph peak. The US Soil Conservation Service (SCS) method (USDA-NRCS 2007) uses a dimensionless unit hydrograph (DUH) to determine the variation of the basin response in time. Full analysis gives a DUH curve which is smooth, but a simplified procedure to determine an appropriate triangular form is also suggested.

Where a catchment is too large or heterogeneous to develop a single unit hydrograph to represent the whole catchment, or where the conditions over a substantial length of the river system are required, then a distributed catchment model may be required. These connect and route the contributions to the flood from several sub-catchments in order to simulate overall flood conditions. The unit hydrograph approach can provide the response of each of the sub-catchments within the models, but care needs to be given to the choice of appropriate rainfall conditions.

The use of distributed modelling is essential for catchments where the hydrological response is not homogeneous because of spatial variations in soils, geology, land-use and topography. Also, where the catchment is large compared with the size of the typical storm, distributed models should be considered if the spatial variation of the precipitation can be estimated.

There are many distributed catchment models in use for flood estimation. They may be either stand-alone applications or integrated into larger modelling systems. The same models can, in principle, be used for all flow conditions, provided that they include the key processes that operate under intense rainfall e.g. a limit on infiltration rate and non-linear surface flow routing. The simulation must use a timescale appropriate to the scale of the catchment. The time to peak of the runoff and the flood modelling may require a finer temporal resolution than the daily time interval common in water resource applications.

A recent extension of distributed modelling has been the integration of damage estimation with flood modelling, (Cunha et al. 2011). This assessment incorporates both river data and high-resolution remote-sensing information. The model parameters are directly related to standard descriptions of the physical properties of the catchment and river system and this obviates the need for calibration in the absence of detailed local data.

Continuous hydrological simulation

Continuous hydrological simulation requires estimated rainfall series over a long period. This poses some important challenges, principally in terms of the computational resource required. The steps in the approach are typically:

- delineation of the catchment boundaries and significant sub-catchment units
- establishment of an appropriate runoff model for continuous simulation
- generation of a long time series of rainfall using a stochastic rainfall generator
- simulation of the corresponding flow time series
- frequency analysis of the flow time series.

Distributed catchment models provide one means of undertaking continuous simulation of flow generation from precipitation in the context of evaluating climate change impacts on flooding. This is done by coupling catchment models with downscaled spatial rainfall fields taken from climate scenarios. Alternatively continuous simulation models may be based upon a regular rectangular grid. Some examples of the approach are in Australia (Droop & Boughton 2003), in Switzerland (Viviroli et al. 2009a; Viviroli et al. 2009b), in the UK (Faulkner & Wass 2005) and in the US (Soong et al. 2005). These examples all use different hydrological process models to simulate the runoff. Faulkner and Wass provide a short-cut to the generation of the flood flow sequences from a 1,000 year time series of synthetic rainfall. They do this by selecting only the largest precipitation events for full simulation and so concentrating the analysis on the more extreme events.

Continuous simulation provides a means of assessing the flood frequency in complex catchments and in ungauged catchments, provided that the parameters for the runoff model can be transposed from experience elsewhere. An important part of the verification of the continuous simulation approach is the ability to replicate observed flood frequency relationships (Calver et al. 1999). Although it is the subject of much current hydrological research, continuous simulation is still not used extensively in routine design practice, probably because of the greater time and resources required for the complexity of this approach.

With a suitable length of synthetic, or observed, rainfall series, continuous simulation is a practical means of assessing design floods up to a probability level of around 1 per cent on modest sized catchments, say of 5,000km^2 or less. It does, however, provide an approach for estimating the change of flood frequency in response to the effects of climate change on the type, amount and seasonality of precipitation. Another application is in the assessment of the effects of changes in land surface conditions (Feyen et al. 2006). Feyen et al. present an application of the European LISFLOOD hydrological model of the whole of Europe as part of a study to understand the potential impacts of climate change at the scale of the EU.

4 Flood Risk

What is flood risk?

The importance of language

A difficulty with the terminology of "risk" and so of flood risk management is that it has been developed across a wide range of disciplines and activities. When discussing flood risk it is essential to recognise that the professional communities involved in flood management now attach special meanings to several common English words. Technical distinctions are made between words which, in common usage, are normally treated as synonyms. Without appreciating the differences between the professional meanings and the common understanding there is scope for misinterpretation and misunderstanding. Moreover, flood risk management may involve professionals from different disciplines each of which may have its own use of technical terms and the meanings may differ subtly across cultures, national languages and in translation.

In everyday use the word "risk" often means the chance or probability of something occurring, such as flooding, without considering the severity of its effects. Another common usage of "risk" is to describe potential adverse outcomes by asking "what are the risks in this?" without considering their likelihood. However, in the context of flood risk management, and as defined in national policy and legislation, the word "risk" has the sense of a combined assessment of both the chance of flooding and its impacts. "Risk" is not a synonym for probability nor a description of what may cause an adverse outcome. For example, Article 2(2) of the European Directive on the assessment and management of flood risks (EC 2007) defines flood risk in the following way:

Flood risk means the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event.

In other contexts the descriptions used in relation to flooding for professional purposes will not accord with common understanding of the same words. Table 2 gives the narrative terms used in the UK as set out in Planning Policy Statement PPS 25 (DCLG 2010) to describe the likelihood of floods. The terminology shows much greater caution than the common everyday usage of terms like "highly probable". To set these probabilities into an every-day context, there are even-odds, i.e. a 50-50 chance, of experiencing a "high" probability condition at least once over a lifetime of 69 years.

Table 2 Descriptions of probability in UK Planning Policy PPS 25

PPS 25 Description of probability	Annual percentage probability range of the condition
High	More than 1 per cent
Medium	Between 0.1 per cent and 1 per cent
Low	Less than 0.1 per cent

A jargon word might also be taken from one discipline into another and its common meaning obscures the intended concept. An example is the word "fragility" in the context of reliability analysis of flood defences. The fragility curves for components of flood defences express their probability of failure under particular flood conditions. An additional problem with the word fragility in this context is that a flood risk manager does not naturally wish to communicate the fragility of a flood embankment, but rather its reliability, strength and safety.

As further illustration we might quote the word "dike" or "dyke". The first definition in the Oxford English Dictionary for this word in common English usage is for a watercourse. The second definition is for a bank or embankment. However, within English translation of the use of the word from Dutch practice an embankment is meant, not a watercourse, and this usage is becoming standard in many internationally authored documents.

A common framework for analysing flood risk

Here we start from the definition of flood risk in the European Directive (EC 2007) as given above. Risk is the combination of the probability of a flood together with its potential adverse consequences. In the past, the planning of flood defences only considered certain sources of floodwater, e.g. the main river or the sea. Today it is recognised that many of the consequences of flooding are the same whatever the sources of flood water and so a full picture of flood risk needs to consider the combination of the impacts of all potential sources of flooding to an area. To undertake this combined approach we need to identify what may cause the hazard of flooding to occur, how often this might happen and the effects of the flooding. Thus to evaluate the risk, separate consideration needs to be made of the four generic components:

- the nature of the sources of the flood hazard
- the pathway which the floodwater takes from the source to those affected
- the exposure of people, property and the environment to the flood hazard
- the consequences of flooding through consideration of the vulnerability of people, assets etc. to damage should the hazard be realised.

This framework is called the source-pathway-receptor-consequence (SPRC) model for flood risk analysis and it underpins the approach to flood risk management in the UK and many other European countries.

In terms of flooding, a description of the nature of the hazard may include considering the following questions:

1. Can the land flood and what is the extent of the area affected?
2. What are the sources of flooding and how often does flooding occur from each of the sources?
3. How deep is the flooding, how rapidly does the flood rise, how fast does the water flow and how long does the flooding last?
4. Can any warning be given and, if so, can those affected take any reasonable actions to reduce their exposure to the hazard?

These questions enable a fuller description of the potential damages to be prepared. For example, some agricultural crop losses are sensitive to the duration of the inundation, the damage to buildings and the potential for loss of life depend upon the depth and velocity of the flood waters, etc.

Table 3, which is extended from (Samuels 2006), illustrates the different effects of floods from a variety of flooding sources and on a range of geographic scales. An understanding of the overall risk to a community, region or nation can be built up through the source-pathway-receptor-consequence analysis to integrate all the potential types and sources of floods and their consequences.

Table 3 Categorisation of flooding hazards and potential impacts

Type of flood	Type of event or frequency	Number of properties affected	Geographic Distribution	Type of damage	Type of mitigation
River Flash Flood	Summer storms	1-500+	• Small steep river catchments • May trigger other hazards e.g. landslides and mudflow	• Inundation damage to buildings and contents, vehicles written off • Buildings and bridges destroyed • Campsites and caravan parks particularly vulnerable • Possible significant loss of life (e.g. Sarno IT, 1998).	• Flood warning service • Community preparedness • Land use regulation • Land management practice
Lowland river flood (Basins up to 10000 km^2)	Winter season rainfall, spring snowmelt	1-500+ Major towns and cities may give larger numbers	• River flood plain • Flooding in one or more river catchments at any one time	• Inundation damage to buildings and contents, vehicles written off, possible structural damage. • May lead to locally significant displacement of population • Deep flooding possible behind raised defences. • Disruption to critical national infrastructure (water, power, telecommunication, transport)	• Hard defence measures • Flood storage • Flood warning service • Land use regulation • Emergency evacuation
Major river basins up to 250000 km^2	Seasonality depends upon basin and climate	10,000+ Major towns and cities give large numbers	• River flood plains • Trans-national basins • Flooding in one or more river catchments at any one time • Flash floods in headwaters	• Inundation damage to buildings and contents, vehicles written off, possible structural damage. • Major infrastructure disrupted • May lead to large displacement of population (approx 250,000 for Rhine floods in 1995). • Deep flooding possible behind raised defences. • Economic loss for event significant in terms of national economic growth rate (> 0.1% GDP)	• Hard defence measures • Flood storage • Flood warning service • Land use regulation • Emergency evacuation
Coastal (surge and wave)	Winter season	1-500+ Major towns and cities may give larger numbers	• Coastal fringe / estuary / mapped flood risk zone • Flooding possible over large lengths of coast (e.g. 1953 storm)	• Deep flooding possible behind raised defences. • Inundation damage to buildings and contents • Possible loss of life (2000+ in 1953) • Major disruption possible from storm surges • Single storey dwellings, campsites and caravan parks particularly vulnerable • Vehicles written off	• Hard defence measures • Soft engineered defences • Storm-tide warning service • Land use regulation • Emergency evacuation
Groundwater	Prolonged seasons of rainfall	Small clusters	• Certain geologies (limestone, chalk, sandstone etc) • Outside main river floodplain	• Inundation damage to buildings and contents, especially basements • Long duration inundation damage (weeks or months)	• Flood proofing • Pumping from properties • Land use regulation
Pluvial floods - overland flow	Prolonged heavy rainfall	Isolated or small clusters	• Hill slopes • Outside main river floodplain	• Inundation damage to buildings and contents, especially basements	• Flood proofing • Pumping from properties • Land use regulation

Type of flood	Type of event or frequency	Number of properties affected	Geographic Distribution	Type of damage	Type of mitigation
Pluvial floods - storm and highway drainage	Intense storms – especially in summer	Isolated or small clusters Urban areas	• Anywhere adjacent to roads or urban areas	• Inundation damage to buildings and contents, especially basements • Possibly vehicle accidents	• Routine maintenance of watercourses and drainage systems • Sustainable drainage systems
Pluvial floods - minor water-courses	Common	1-20+	• Outside main river floodplain • Blocked culverts	• Inundation damage to buildings and contents, especially basements	• Land use regulation • Hard defence measures • Routine maintenance of watercourses
Water mains burst	Any time	Small clusters	• Anywhere	• Inundation damage to buildings and contents, especially basements	• Asset inspection and renewal by water service providers
Sewerage e.g. by blockage or collapse	Any time	Isolated or small clusters	• Anywhere • Outside main river floodplain	• Inundation damage to buildings and contents, especially basements • Foul sewage contamination	• Asset inspection and renewal by water service providers
Dam break	Any time but infrequent	1-1,000+	• Specific river valleys • Outside main river floodplain	• Inundation damage to buildings and contents, vehicles written off, • Destruction of buildings, destruction of bridges, major infrastructure disrupted • Potential significant loss of life within 25 km of dam	• Monitoring on-site. • Risk management by owners • Contingency plans • Emergency evacuation
Tsunami	Any time but infrequent	1-10,000+ depending on location	• Coastal zones and hinterland	• Inundation damage to buildings and contents, vehicles written off, • Widespread agricultural damages • Destruction of buildings, major infrastructure disrupted • Potential significant loss of life	• Contingency planning • Spatial planning • Warning systems • Emergency evacuation

Definitions of key concepts

The European FLOODsite research project compiled a terminology (Gouldby & Samuels 2009) for many concepts around flood risk and flood risk management, initially to aid understanding within the research team. However the definitions have found wider use within EU Member States. Gouldby provides the following key definitions given in Table 4.

Table 4 Definitions from the FLOODsite Language of Risk

Concept	Definition
Flood	The temporary covering of land by water not normally covered by water
Hazard	A physical event, phenomenon or human activity with the potential to result in harm. A hazard does not necessarily lead to harm
Receptor	Receptor refers to the entity that may be harmed (a person, property, habitat etc.). The vulnerability of a receptor can be modified by increasing its resilience to flooding.
Exposure	Quantification of the “receptors” that may be influenced by a flood (for example, number of people and their demographics, number and type of properties etc.).
Consequence	An impact such as economic, social or environmental damage/improvement that may result from a flood. May be expressed quantitatively (e.g. monetary value), by category (e.g. high, medium, low) or descriptively.
Vulnerability	Characteristic of a system that describes its potential to be harmed. This can be considered as a combination of susceptibility and value.
Risk	Probability multiplied by consequence in which the multiplication is to be understood as including the combination across all floods.
Flood risk management	Continuous and holistic societal analysis, assessment and mitigation of flood risk.
Risk analysis	A methodology to objectively determine risk by analysing and combining probabilities and consequences
Risk assessment	Comprises understanding, evaluating and interpreting the perceptions of risk and societal tolerances of risk to inform decisions and actions in the flood risk management process.
Risk management measure	An action that is taken to reduce either the probability of flooding or the consequences of flooding or some combination of the two.
Scenario	A plausible description of a situation, based on a coherent and internally consistent set of assumptions. Scenarios are neither predictions nor forecasts. The results of scenarios, unlike forecasts, depend on the boundary conditions of the scenario.
Strategy	A strategy is a combination of long-term goals, aims, specific targets, technical measures, policy instruments, and processes which are continuously aligned with the societal context.
Sustainable flood risk management	Sustainable flood risk management provides the maximum possible social and economic resilience against flooding, by protecting and working with the environment, in a way which is fair and affordable both now and in the future.

How flood risk is assessed and understood

Source, pathway, receptor and consequences framework

Flood risk may be analysed by following the source-pathway-receptor-consequence chain. So for example, in the event of heavy rainfall (the source) flood water may propagate across the flood plain (the pathway) and inundate housing (the receptor) which may suffer material damage (the harm or consequence), see Figure 10. At each step in this chain the probability of events, conditions or assumptions are assessed, either as fixed conditions or within a probabilistic framework.

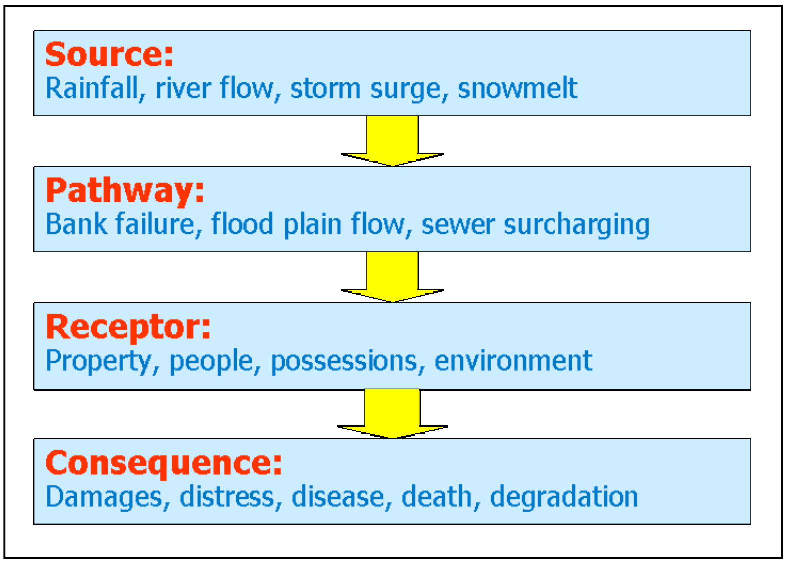

Figure 10 The Source Pathway Receptor Consequence chain (source HR Wallingford)

In the context of flooding, the source of risk is the heavy rainfall, snowmelt, river discharge, storm surge or whatever gives rise to the potential for flooding. A characteristic of flood sources is that there is usually little or no ability to control the frequency of occurrence or the severity of the source. For a source of a hazard to cause damage, a route or "pathway" is needed. This is how the source reaches the "receptor" that is exposed to the hazard. There may be several pathways from a source to a particular receptor. A receptor may experience flooding from more than one source by different pathways. The pathway may include river channel, floodplain or embankments if submerged or breached. The performance and characteristics of the pathway can be modified through engineering and maintenance activities and the pathway may only transmit flooding from the source in certain circumstances, perhaps through the operation of a structure or some other flood management intervention. The receptor is the person, property or other "asset" that can experience damage or harm from the flooding. The consequences are damages, whether capable of expression in monetary terms or not. However, damages may be offset by possible benefits from the flooding. The receptors of flooding can be influenced through strategies, policies and information which change the frequency of exposure of the receptors to flooding and the consequences of flooding may be altered by changes in the design of flood protection measures.

In essence, flood risk analysis provides a static evaluation of the risk, measured through a summation or an integration of flood probability and an evaluation of the consequences. This evaluation of the risk can be for either current hydrometeorological and socio-economic conditions or for some future scenario. Flood risk can be modified by altering the character of the source, pathway, receptor or consequence through a variety of measures.

Thus the source-pathway-receptor-consequences framework provides a means of examining the difference in risk from potential future changes in climate or economic development, coupled with the effects of structural and non-structural measures for mitigating flood risk.

Difference between idealised and actual performance of flood defences

To obtain a realistic view of flood risk in an area it is important to take account of the influence of tolerances, such as freeboard, which are incorporated in the design and construction of physical defences and also of operational factors. The traditional assumption for the design of flood defences is that they perform perfectly up to the design standard and then they have no function for more severe events. This idealised behaviour differs significantly from what happens in practice. For all types of physical defence there is some probability that the defences will fail in an event less severe than the design standard, through breaching or some other structural failure. In contrast, if the final construction includes some freeboard above the design level, then the defence may still provide protection for some events above the design standard. Likewise, for systems of demountable flood defences, such as removable temporary walls, there is a finite probability that the defences will not be erected properly through operator error, or not be erected at all if, for example, transport disruptions prevent the defences being taken from their storage locations to the site. Figure 11 illustrates the performance for a hypothetical case.

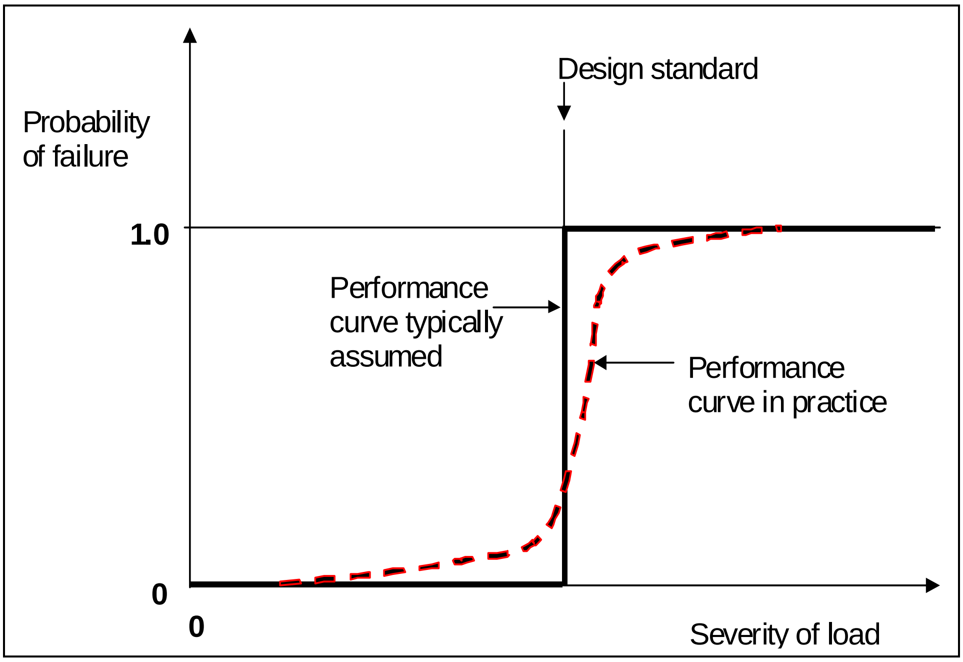

Figure 11 Probability of failure curve for a flood defence (source HR Wallingford)

A whole systems approach to risk analysis is needed to incorporate the behaviour of real flood defences (Hall et al. 2003). In a systems approach all the potential failure mechanisms are identified along with their likelihood and consequences. This provides a full appreciation of the magnitude of the risk and enables the weak links, or hot spots, to be identified.

Acceptable, tolerable and intolerable risk

Intuitively it might seem that risks with a similar overall value in terms of combination of likelihood and impact would have a similar significance, but this is often not the case. It is important to understand more of the nature of the risk, distinguishing between rare, catastrophic events and more frequent less severe events. Other relevant factors include the difference in how society and individuals perceive risks and the degree of uncertainty in the assessment.

Any flood management decision involves weighing-up many, often competing, factors. Inherent in this process are decisions regarding the significance or acceptability of different risks made by both the decision-makers and the broader community of stakeholders as to which risks are "unacceptable", "tolerable" or "broadly acceptable". These perceptions will reflect the stakeholder values and preferences. For example, an environmentalist may be prepared to accept greater economic risk compared to a financier who may tolerate a greater risk of environmental damage. Perceptions will also reflect the inherent approach of the decision-maker towards risk, some being more risk averse than others. Therefore, when considering the "significance" of a risk, reference must be made not only to the numerical value of the combination of probability with consequence, but also to how it will be perceived by society or the individual. The question which must be addressed is “the significance for whom?”, which leads to consideration of the distinction between individual and societal risk.

An individual risk arises from a voluntary action of the individual and lies under his/her control. In contrast a societal risk is experienced by a segment of the population as a whole and any individual in that population has little or no control over his/her personal experience of an adverse outcome from that activity.

As an illustration of the difference between individual risk and societal risk, consider the likelihood of fatalities in an accident, per km travelled by different modes of transport. Where there is no direct individual control, the management of the transport hazard is ceded to another, the train driver or airplane pilot, and the individual will in general not tolerate the same likelihood of an accident as in a situation which is under his/her direct control. In the UK it is not acceptable for 50 people to die in a rail or air crash even once in 10 years, but that number may die in less than a week on the nation’s roads. Acceptable risks are likely to be higher if the activity is voluntary and the person concerned has control over it, like driving a car. Moreover, even when not participating in an activity, fear or dread of an accident in general may lead to a sense of outrage when an accident occurs which involves many casualties and this leads to some form of public investigation, changes in policy or safety management.

Flood risks are generally societal risks and their management is seen as the responsibility of professionals or public authorities. Thus there is often an expectation that after a flood affects a community a flood defence scheme will be promoted with some form of national or local government funding. This view of flooding as a societal risk contrasts somewhat with the principal cause of fatalities in flash floods which arise from individual actions, such as being trapped in a car trying to negotiate the floodwater. This has the nature of an under-estimated individual risk.

One pragmatic approach to the management of societal risks is to assess the risks as "acceptable", "tolerable" or "intolerable". If the risk is judged to be intolerable then action will be taken to reduce the risk, often by reducing the likelihood of occurrence, regardless of the cost, or nearly so. If the risk is tolerable, then risk management activities will concentrate on reducing the risk "as low as is reasonably practicable" (ALARP). Often this involves an assessment of the costs and benefits of risk reduction at public expense. If the risk is acceptable, then the risk management activities will seek to maintain this position. Figure 12 illustrates this approach.

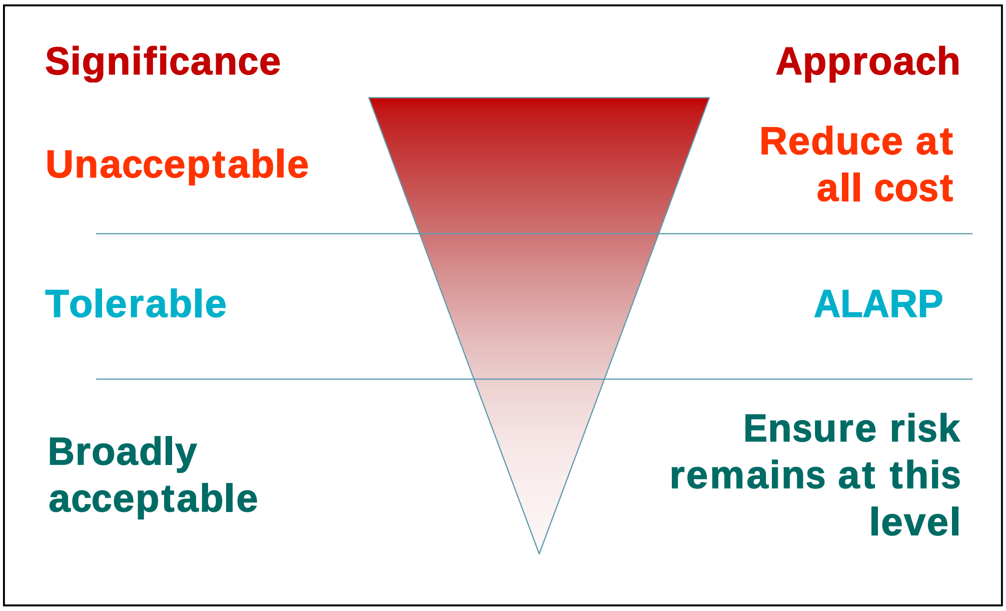

Figure 12 General approaches to the management of flood risks (source HR Wallingford)

Flood risk in the future

Weather and climate change

It is important to recognise that the world's climate has never been constant and that variations and changes in the climate have occurred over a range of time scales and from a variety of causes. The current international and popular concern with climate change relates to alterations in the climate over the past 200 years or so that can be attributed to anthropogenic causes. These relate particularly to the increased concentration of so-called greenhouse gases (GHG) in the atmosphere which leads to warming through trapped incident solar radiation. This global warming leads not only to a rising trend in the global mean temperature but potentially to greater variability in weather. There are also regional variations around this trend caused by changes in weather patterns and alterations to the hydrological cycle (Barry & Chorley 2003). There are many GHGs and these are often represented as equivalent, in their effect in warming the atmosphere, to increases in carbon dioxide CO_2. However, not all emissions lead to warming, some atmospheric emissions tend to cool the climate through increased reflection of incident solar radiation back into space. Changes in the climate also interact with physical and biological processes on the land surface and in the oceans with feedback into the atmosphere. The scientific understanding of climate change has increased markedly since the commencement of the activities of the Intergovernmental Panel on Climate Change (IPCC) and the IPCC publication of a series of assessment reports in 1990, 1995, 2001 and 2007.

Any change in the climate is an important factor in the evolution of flood risk. Inland flooding is affected by changes in the type, intensity and frequency of precipitation. Coastal flooding is affected by sea level rise, storm surge conditions and changes in storm wave conditions and direction.

In this context it is important to distinguish between climate and weather. Weather is the short-term meteorology of an area, with hourly and daily variation. In contrast climate describes the typical meteorology over a much larger spatial scale and longer time-scale. The climate for a region has a spatial context distinguishing the characteristic meteorology of one region from another, with descriptions such as "humid sub-tropical", "marine west-coast" or "Mediterranean" (Barry & Chorley 2003). In another sense, normal climatic conditions for a particular month or season are the average of conditions for the relevant period over past decades.

Weather can be forecast using detailed computer based models of atmospheric conditions, with generally good forecasts for two days ahead, but increasing uncertainty as the forecast horizon increases. The root cause of the unpredictability of weather much more than about two weeks ahead lies in the so called "butterfly" effect which describes the accumulation of the influence of small initial uncertainties until they dominate the forecast. Fundamentally the fluid dynamics found in the atmosphere are turbulent and chaotic and this behaviour is reflected in all numerical predictions.

The success of numerically based weather predictions lies in readjusting the computations regularly by assimilating data on actual weather conditions from the worldwide meteorological network. It is common practice now to provide a range of perhaps up to 50 forecasts each based upon slightly different, but plausible, interpretations of the initial atmospheric state. Such forecasts illustrate a range of potential weather conditions, and allow statements on the probability of certain types of weather being experienced, such as a 70 per cent chance of 50mm or more rain in the next 24 hours at a particular location.

Although the detailed weather for weeks, months or years ahead cannot be forecast, the trend of change in average conditions can be assessed with greater certainty through the use of a general circulation model (GCM), the "general circulation" being a term for the global-scale three-dimensional atmospheric behaviour. The current generation of GCMs couple atmospheric, ocean and land surface conditions, to incorporate feedback between these global systems. In principle, the same GCM may be used for both weather forecasting and for climate simulation but with the modelling using different spatial and temporal resolutions. Internationally, there are several climate modelling centres including the Hadley Centre of the UK Met Office. These GCMs use differing computational methods and parameterisation of the physics of the atmosphere, ocean and land surface. GCM predictions of long-term changes in atmospheric conditions will vary according to the GHG emissions scenario being considered, with the scenarios being set out in the Special Report on Emission Scenarios, SRES. The SRES scenarios cover a wide range of the main driving forces of future GHG emissions, from demographic to technological and economic developments (IPCC 2000).

The IPCC Fourth Assessment Report provides an expert analysis of publications on many peer-reviewed GCM studies and impact analyses. The reports are available from the World Meteorological website (http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml). The main report gives a summary for policymakers and is based upon the detailed reports of each of several working groups. The discussion of the recent trends, and the projections of future changes in climate, includes an assessment of the degree of confidence in the observations and predictions as given in Table 5.

Table 5 Descriptions of likelihood used in the IPCC Fourth Assessment Report

Description	Probability of occurrence,
Virtually certain	*> 99%*
Extremely likely	*> 95%,*
Very likely	*> 90%,*
Likely	*> 66%,*
More likely than not	*> 50%,*
Unlikely	*< 33%,*
Very unlikely	*< 10%,*
Extremely unlikely	*< 5%*

The summary for policymakers from the working group dealing with the physical science base (IPCC 2007) gives several conclusions relevant to the impact of observed climate changes on flood probability, including:

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.

At continental, regional, and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones.

Amongst the projected regional-scale changes in features of the climate, the impacts on flood sources including sea level and precipitation are described as follows:

It is very likely that …….. heavy precipitation events will continue to become more frequent.

Based on a range of models, it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures. There is less confidence in projections of a global decrease in numbers of tropical cyclones.

Extra-tropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation, and temperature patterns, continuing the broad pattern of observed trends over the last half-century.

Increases in the amount of precipitation are very likely in high-latitudes, while decreases are likely in most subtropical land regions (by as much as about 20 per cent in the A1B scenario in 2100, see Figure SPM-7), continuing observed patterns in recent trends.

If radiative forcing were to be stabilized in 2100 at A1B levels, thermal expansion alone would lead to 0.3 to 0.8 m of sea level rise by 2300 (relative to 1980–1999). Thermal expansion would continue for many centuries, due to the time required to transport heat into the deep ocean.

Figure 13 is produced from the IPCC report.

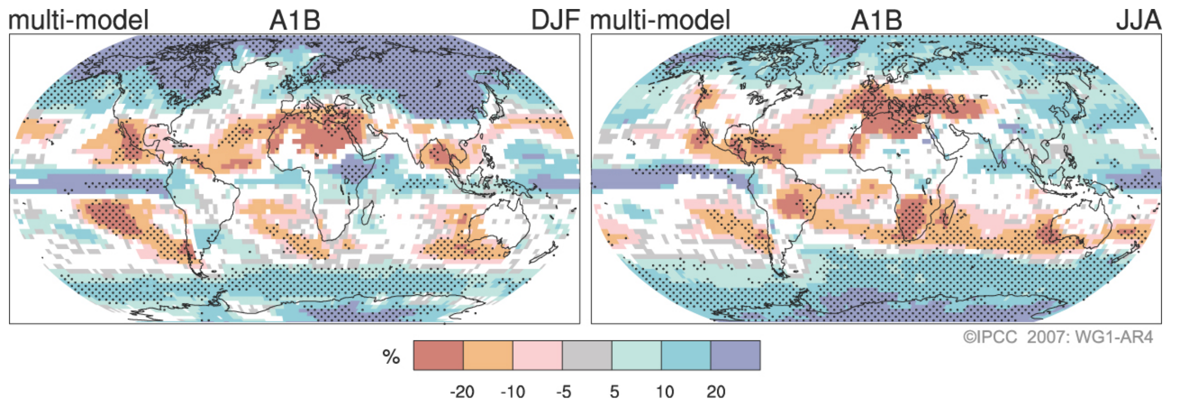

***FIGURE SPM-7.** Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change.*

Figure 13 Relative changes in precipitation (source IPCC 2007)

In 2009 the UK Climate Impacts Programme (UKCIP) published a higher resolution set of climate scenarios for the UK (Jenkins et al. 2009). Many of the UKCIP results provide a probabilistic view of the future scenario outcomes from an approach using a regional climate model with a basic spatial resolution of 25km across the country. This is an order of magnitude finer than the base resolution of the GCM analysis given in the IPCC assessments. A national weather generator provides even finer-scale results down to a resolution of 5km. These results provide greater detail at a scale relevant to policy development and adaptation decisions. For flooding impacts, the general pattern seen in the IPCC multi-model comparison persists. The UK can expect dryer summers and wetter winters, particularly in southern England.

Impacts of climate change on river flood defence infrastructure

Climate change will affect flood risk management activities in several ways, from the methods of analysis through to the maintenance of flood defence infrastructure. In terms of analysis of flood probability, most standard statistical methods assume that the data on flood flows can be assumed as statistically "stationary". This means that there is no long-term trend in the mean or variance of the flood data series. If, in the future, precipitation patterns change, the assumption of stationarity may not be valid and alternative methods of estimating future flood probability will be needed. Although in the UK the current evidence from climate models is that future precipitation will increase from the 1960 to 1990 average currently used as the baseline climate, care should be taken in adjusting flows sampled from much longer time series as there is potential for some trend in the flood series to be present prior to 1960. For example, a trend has been established for the floods on the River Thames which have been measured since the 1880’s. Climate change will not only affect the volume of precipitation in extreme events but may also influence the hydrological response of the catchment through changes in typical pre-event soil moisture conditions, evaporation and rainfall intensity.

However, climate change is not the only potential cause of non-stationarity in the historic flood record. Water levels and discharges can also be influenced by major flood defence schemes such as the construction of storage reservoirs and embankments and works to increase channel capacity. Influences also come from large-scale land use change in a catchment such as urbanisation. These changes to the watercourse and catchment influence flood peaks, and the magnitude of the changes to peak levels varies with the severity of the flood. Often the greatest influence is seen in the more frequent flood events.

For river channels, climate change may have several indirect impacts which will influence their conveyance in flood conditions including:

- changes in vegetation which alter the flood resistance
- changes in channel morphology arising from changes in sediment delivered to the channel and the sediment transporting capacity of the channel.

The performance of river flood defence embankments may be affected by long-term climate change in several ways and this emphasises the importance of the inspection and maintenance regime. Potential impacts in the long-term include:

- cracking of embankment soils as a result of increased frequency of high temperatures
- changes to the resistance of natural rivers when hotter, drier summers affect vegetation
- changes in river bank erosion as a result of changed hydraulic conditions.

Hydraulic structures on rivers may also be affected by climate change, again emphasising the importance of the inspection and maintenance regime. Potential impacts in the long-term include:

- bridges may experience a) general scour which exposes foundations, b) enhanced local scour from changes in sediment load, c) changes in local flow conditions and d) increased potential for blockage from debris transported by flood flows
- weirs may experience a) increased sedimentation upstream and b) local erosion of bed and banks downstream caused by long-term increases in the amount of energy dissipated
- land drainage pumping stations may be influenced by a) the need to operate against greater downstream head conditions in tidal water courses as a consequence of sea level rise and b) changes in tide lock periods which affect the balance between channel conveyance and the storage required for effective flood risk management in lowland areas
- dams may require a) increases in the capacity of spillways to take into account changes in the estimated probable maximum flood and b) enhanced protection measures for wave overtopping to take into account changes in wind speeds.

Social change

Social and economic development has a strong influence on flood risk, principally through changing the consequences of flooding when it occurs. Some influences are more readily apparent than others. For example, the accumulation of personal property with growth in prosperity in an area subject to a flooding hazard causes an increase in the potential for flood damage. Also, social changes, which decrease community identity and cohesion, increase the consequences of flooding as individuals and businesses become less resilient and take longer to recover from floods.

The UK Flooding Foresight project (OST 2004) assessed the relative importance of many drivers of flood risk in the future and identified that socio-economic factors were amongst the strongest. The social impacts driver of future flood risk includes the following statement:

….. includes the risks to life and health, the ‘intangible’ impacts of flooding, the vulnerability of different groups and impacts of flooding on community cohesion.

This driver was found to be the single most important factor out of 17 in increasing future flood risk in three of the four scenarios examined and was the third in the remaining one.

One important factor in terms of social resilience to flooding is the progressive erosion of local knowledge of flooding leading to a decrease in people's capacity to adapt to changes in risk. This knowledge not only concerns the nature of the area but also its management. It is fundamental that the citizens not only understand how to behave in emergencies, but also that they anticipate and mitigate the potential consequences of dangerous flood events. The loss of this local knowledge may arise from several factors including greater mobility in the population and from the provision of effective flood defences which render an area safe from most floods and promote complacency.

Given the importance of social and economic factors in determining current risk and in influencing future increases in flood risk, effective flood risk management in the future will only be effective if the public are involved and knowledgeable.

Policy frameworks

In the decades since the Earth Summit at Rio in 1992 (UNCED 1993), sustainable development has gained international acceptance and commitment as a fundamental policy aim for national governments and supra-national institutions. The classic definition of sustainability was formulated in the Bruntland report (Bruntland 1987) as development which:

…meets the needs of the present without compromising the ability of future generations to meet their own needs.

There is still a need to promote further understanding of concepts relating to sustainable development with the general public even though these have achieved general acceptance with the professional community through the incorporation into national policy and legislation, for example through the implementation of the European Directive on the assessment and management of flood risks (EC 2007)). The pathway for sustainable development and management of flood plains must be achievable technically, economically, socially and politically. It will require a broad view of the interventions in the river catchment rather than local single-issue design or management. Traditionally planning has been restricted to a select few politicians and professionals but in order to engage with the range of players involved, planning needs to be opened to an informed public.

There is a different philosophical basis for the provision of structural measures and non-structural measures as instruments for flood risk management. Historically man has sought to tame floods through the construction of embankments and reservoirs which provide security for occupants of flood plains. However, non-structural measures and instruments, such as flood plain zoning, spatial planning, water retention, infiltration standards for new development and flood warnings, recognise that flooding will still occur as part of the natural processes within the river basin. Difficult choices may arise in the management and protection of existing development and infrastructure on the flood plains of rivers where this conflicts with the policy of sustainable flood plain management. It is important to recognise that there are many players with differing interests in the management of flood risks.

The UK Future Flooding Foresight

The UK Flooding Foresight project (OST 2004) investigated the future of flooding in the UK and led to significant development of national policy in terms of the management of flood risks. This review was undertaken by an expert team assembled by the UK Office of Science and Technology over the period October 2002 to March 2004. The project investigated drivers, responses and scenarios for flood risk over a timescale of about 100 years to develop public policy and to assess expenditure. The UK was divided into 10km squares and flood risks were analysed for four socio-economic scenarios, which were linked to global emission scenarios and simulations of future climatic conditions. The scenarios represent different policy frameworks for the country and considered a) world markets, b) national enterprise, c) global sustainability and d) local stewardship (DTI 2002). The Flooding

Foresight project considered all types of flooding including floods in urban areas, in rivers and estuary environments and in coastal regions. Drivers of flood risks were identified and ranked under each of these scenarios and the potential flood damages estimated for the 2080s.

Substantial differences emerged between the scenarios, with the damage increasing in all scenarios if current policies are maintained. The annual flood damage was estimated as about 0.6 billion pounds for 2002 conditions, with this rising to over 20 billion pounds without additional mitigation strategies in the worst scenario connected with world markets. Future flood risks were shown to depend strongly on the assumptions made about global emissions of greenhouse gases and established a clear link between international policy and impacts at the national scale.

The summary report (OST 2004) posed many questions to policy makers such as:
1. Should the increasing levels of flood risk be accepted or actions taken to reduce them?
2. How important is the management of climate change to the risks faced from flooding and how best can this management be achieved?
3. How should land be used in balancing the wider economic, environmental and social needs against creating a legacy of flood risk?
4. What is the balance between societal responses to flood risk and the implementation of enhanced structural defences?
5. Who should pay for flood defence and where is the balance between government, developers, the individual and insurance?

The recommendations from this report led to new government policy directed at the management of flood risks rather than providing protection. The policy is called Making Space for Water (Defra 2008), and this policy is now enshrined in the legislative framework of the Flood and Water Management Act (2010).

5 International action and cooperation on flood risk management

Flood risk has international dimensions

Rivers and floods are not constrained by administrative borders either within or between nations and so floods and flood risk management can have significant international dimensions. The river Danube basin, for example, is the most international basin in the world with parts of its catchment in a total of 18 countries. Some reaches of the main river act as an international border between neighbouring states. Flooding in Bangladesh arises from its situation at the confluence of three major rivers draining into the Bay of Bengal, the rivers Ganges, Jamuna and the Meghna. Over 90 per cent of the water that drains into the Bay of Bengal from Bangladesh has its origins outside the country.

When exceptionally severe floods hit any country, international relief agencies act where the situation overwhelms the national capacity to respond. For example, flooding in Pakistan began in July 2010 following unusually heavy monsoon rains over the Indus basin and directly affected about 20 million people, with approximately 1,800 fatalities (ReliefWeb 2010). International news reports during the event showed widespread destruction of property and infrastructure with devastating effects on the livelihoods of the rural population. This led to one of the largest UN requests ever for emergency aid.

There are several international initiatives to improve the management of flood risks. They provide mechanisms for cooperating in the management of river basins and principles for improving resilience to the impacts of floods through exchange of information and through common legislation.

The UNISDR and the Hyogo Framework for Action

The United Nations International Strategy for Disaster Reduction (UNISDR) provides a vehicle for cooperation between governments, organisations and civil society to reduce the effects of disasters on people in all nations. Flooding is one of the major natural hazards that threaten nations across the world and, in January 2005, 168 governments adopted the UNISDR Hyogo Framework for Action (HFA) which is a 10-year plan to make the world safer from all natural hazards. The HFA provides an international blueprint for disaster risk reduction during the decade to 2015. The ultimate goal of the HFA is to reduce disaster losses substantially by 2015 as measured in terms of lives lost, and in the damage to social, economic, and environmental assets. The framework gives a set of guiding principles, priorities for action, and practical means for improving the resilience of vulnerable communities to disasters (UNISDR 2005).

In UNISDR terminology (UNISDR 2009) a disaster is *"a serious disruption of the functioning of a community or society involving widespread human, material, economic or environmental losses and impacts which exceeds the ability of the affected community or society to cope using its own resources.*" Through this definition, whether an event is deemed to be a disaster or not depends upon whether the community or country affected has the economic and social resources available to cope with the event. So disasters and poverty are closely linked. There have been several widely publicised cases of flooding which have caused a disaster as defined in the HFA. Two recent examples are the flooding of the river Indus basin in Pakistan in 2010 and the flooding in river basins in Queensland, Australia in early 2011. In both cases the number of fatalities was small compared with the number of individuals who had their livelihoods disrupted by the floods.

Moreover, the UNISDR terminology describes disaster risk as "*the potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period.*" Thus the exposure to all hazards, including floods, is considered in understanding the overall impact and thus the risk of disasters potentially occurring to a community. The reduction of that disaster risk can then be addressed through the HFA strategy. In disaster risk management and disaster risk reduction it is recognised that the hazards may occur in combination and show dependence and interaction. Such information will identify whether the overall risk is acceptable. The information is essential for identifying critical facilities and infrastructure and for the preparation of emergency plans. The HFA sets strategies for disaster risk reduction for all natural hazards and has five key aims:

- to ensure that disaster risk reduction is a national and a local priority with a strong institutional basis for implementation
- to identify, assess and monitor disaster risks and enhance early warning
- to use knowledge, innovation and education to build a culture of safety and resilience at all levels
- to reduce the underlying risk factors
- to strengthen disaster preparedness for effective response at all levels.

All nations are invited to participate in the programme of the UNISDR and to develop national mechanisms for implementing the HFA strategy. Each country is requested to report progress regularly towards the overall goals (UNISDR 2011).

WMO APFM

The Associated Programme on Flood Management (APFM) is a joint initiative of the World Meteorological Organization (WMO) and the Global Water Partnership (GWP). It promotes the concept of integrated flood management (IFM) as a new approach to flood management (WMO 2009). An important distinction is that the APFM sees integrated flood management in broader terms than the concept of flood risk management as espoused by the EU Floods Directive.

Integrated flood management calls for a major shift from the traditional, fragmented and localised approach of flood defence measures, and encourages the use of the resources of a river basin as a whole. It advocates strategies to maintain or augment the productivity of floodplains, while at the same time providing protective and mitigating measures against losses due to floods. Thus integrated flood management recognises that floods have beneficial effects, as evident in the strategy adopted by Bangladesh, whereas flood risk management concentrates on minimising the negative consequences of floods. Hence the approach of the APFM is to include flood risk management as a component of integrated flood management. The Associated Programme on Flood Management receives financial support from the governments of Japan and Switzerland.

International Flood Initiative

The International Flood Initiative (IFI) was launched in January 2005 at the World Conference on Disaster Reduction in Kobe, Japan which also established the UNISDR. The IFI is a collaboration of several international organisations including the United Nations bodies UNESCO, WMO, UNISDR and the United Nations University together with the international professional societies IAHS and IAHR. Like the WMO APFM, the IFI promotes the concept of integrated flood management considering prevention and mitigation measures and also the positive and negative impacts of floods. The objective of the IFI is to build the capacity to understand and respond to floods by taking advantage of their benefits while at the same time minimising the social, economic and environmental risks. The IFI aims to catalyse the resources and established networks of the UN system, non-governmental organisations, donor agencies and the insurance industry to develop flood management practices that respect the local and national culture and support sustainable development. The IFI promotes five principles:

- the need for living with floods
- equity between all stakeholders
- empowered participation of stakeholders
- interdisciplinary and trans-sector working
- international and regional cooperation.

The IFI works principally through education, training, research, networking and technical assistance. The administration of the IFI is located at the International Centre for Water Hazard and Risk Management (ICHARM) in Tsukuba, Japan.

International river commissions

Many large river basins include the territory of several independent states and the actions of one state in river management can have implications for another. Although this text concentrates on the impact on floods and flood risk management, many other issues are important for the management of international river basins, especially those connected with the availability of water in regions of water stress. Examples of international river commissions include those for the rivers Rhine, Danube, Elbe, the Mekong basin in Asia and the Red River which flows across the border between the US and Canada. These international commissions have their objectives and activities governed by the multi-lateral treaties agreed when they were established. Some commissions, such as the Danube, have specific plans for flood risk management in their basins.

The flood risk management plan for the Danube (ICPDR 2004) outlines a series of actions on a basin-wide basis to restore, where possible, the natural functions of the river Danube. The plan operates through established bi-lateral agreements between neighbouring states and recognises that structural flood defences will continue to play a role in flood risk management alongside flood warning, insurance and individual actions.

European Directive on the assessment and management of flood risks

Since the early 1990's several EU Member States have suffered from severe flooding (Samuels 2006; Knight & Samuels 2007) and this has highlighted the need to manage floods in an equitable manner when they cross national boundaries. As a first step the Water Directors in each Member State prepared a document on "best practices on flood prevention, protection and mitigation" (EC 2003). This best practices document concentrated on principles rather than details and it set the scene for the development of the European action plan on floods in 2004, followed by the European Directive on the assessment and management of flood risks, the "Floods Directive". This important development of European policy on floods finally entered legislation in November 2007 (EC 2007). Article 1 of the Floods Directive describes its objective as follows:

The purpose of this Directive is to establish a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the Community.

The Floods Directive applies to the whole land area of each Member State, and therefore to flood risk management from both rivers and coastal areas. The Floods Directive is aligned with and complements the Water Framework Directive (Directive 2000/60/EC). It requires each Member State to prepare a sequence of assessments, maps and plans that cover the river basin districts within their jurisdiction. In addition, for international rivers, there are specific requirements for trans-boundary collaboration.

The purpose of the preliminary flood risk assessments is to identify those areas where there is significant flood risk and which need to be considered in the other two phases of the risk management cycle. For those areas where there is significant risk, flood maps need to be prepared which show the extent of the flood hazard together with other information that indicates the nature of the risk.

The Floods Directive requires the hazard to be mapped for three cases, a low probability or extreme event flood, a medium probability flood and a high probability flood where appropriate. The medium probability flood has an indicative return period of at least 100 years. The qualification, where appropriate, for the high probability flood is one instance where the Floods Directive leaves a degree of discretion to Member States in the transposition of the directive into national law. Another area of discretion is in the degree to which the risks from flooding from urban storm water drainage systems are included in the mapping and plan preparation. As well as extreme floods, say of a return period of 1,000 years or more, the extreme event scenarios may include the effect of failure of infrastructure such as dams. The flood risk maps must show the flood extent and information on flood depth or level. The maps may also include information on water velocity. The maps cover the extent of the flood hazard and provide information on certain regulated pollutant sources. The maps may also show information on debris and sediments if appropriate.

For all areas where there is significant risk, as revealed in the preparation of the maps, flood risk management plans must be prepared. The purpose of these plans is to define a series of actions to reduce and mitigate the flood risk by focusing on the reduction of potential adverse consequences of flooding for human health, the environment, cultural heritage and economic activity. The flood risk management plans need to take into account the characteristics of the particular river basin. They must consider all aspects of flood risk management, focusing on prevention, protection and preparedness, including flood forecasting and early warning systems. In this context flood prevention means measures such as spatial planning and development control to stop increases in potential flood risk in the mapped areas of hazard. Flood protection is the provision of flood defence infrastructure. The flood risk management plans may also promote sustainable land use practices, seek improvement of water retention and consider the use of sacrificial storage measures through the controlled flooding of certain areas in the case of a flood event.

The Floods Directive has now been incorporated into national legislation in each of the 26 Member States of the European Union. The details for implementation in each Member State differ according to local legislation on water management issues, with responsibilities given to national, regional or local authorities and agencies. The first round of flood risk management plans will be produced in 2015 with the process of risk assessment, risk mapping and preparation of revised management plans being repeated on a six-yearly cycle. (Van Alphen et al. 2009).

6 Flood risk management practice

Principles

Issues relating to the long-term management and alleviation of floods are inextricably linked to river basin management. Galloway has suggested that the management of river basins in a sustainable manner will only be achieved if the following challenges are addressed (Galloway 1998):

- the lack of public understanding of the issues
- rigidity in administrative mechanisms which cut across river basin boundaries
- bureaucracy
- the inclusion of new players in the water sector, e.g. NGOs
- the removal of a bias in project procedures which favour structural solutions
- the lack of interdisciplinary approaches
- the appropriate use of new technologies
- the revoking of outdated legal issues.

Galloway drew his conclusions partly from his report for the US Government into the Mississippi flood of 1993. Some of these themes also occurred in a European context as found in the EC funded EUROflood project (Handmer 1997).

Some of the practical issues involved in achieving sustainable management of rivers are identified in the contributions to the European Concerted Action RIBAMOD (Smidt & van Westen 1997; Borrows et al. 1998). Borrows et al. discuss practices for the sustainable maintenance of rivers and they identify:

- the need for an approach which is linked to other catchment management issues
- the careful timing of maintenance operations
- the training of those involved in river maintenance
- the use of more environmentally sensitive forms of river engineering and bank protection.

There is a need for a holistic approach to flood management that encompasses all phases of the operational and management cycle. The mitigation of flood damage and losses caused by floods does not only depend upon the actions during floods but is a combination of pre-flood preparedness, operational flood management and post-flood reconstruction and review. A review of the impact of the major flooding on the river Oder in Poland, the Czech Republic and Germany (Kundzewicz 1997), led to a crystallisation of the concept of a holistic approach to flood management (Kundzewicz & Samuels 1997). In outline this comprises the following activities.

Pre-flood activities

- flood risk management for all causes of flooding
- construction of flood defence infrastructure, both physical defences and the implementation of forecasting and warning systems
- maintenance of flood defence infrastructure
- land-use planning and management within the whole catchment
- discouragement of inappropriate development within the flood plains
- disaster contingency planning to establish evacuation routes, critical decision thresholds, public service and infrastructure requirements for emergency operations, etc.
- public communication and education of flood risk and actions to take in a flood emergency.

Operational flood management activities

- detection of the likelihood of a flood developing using hydro-meteorology
- forecasting of future river flow conditions from the hydro-meteorological observations
- warning issued to the appropriate authorities and the public on the extent, severity and timing of the flood

- response to the emergency by the public and the authorities.

Post-flood activities (depending upon the severity of the event)

- relief for the immediate needs of those affected by the disaster
- reconstruction of damaged buildings, infrastructure and flood defences
- recovery and regeneration of the environment and the economic activities in the flooded area
- review of the flood management activities to improve the process and planning for future events in the area affected and more generally, elsewhere.

These activities may be viewed as a cycle in time as the period after one flood merges into the planning pre-flood stage of a subsequent event, see Figure 14 (Samuels et al. 2008).

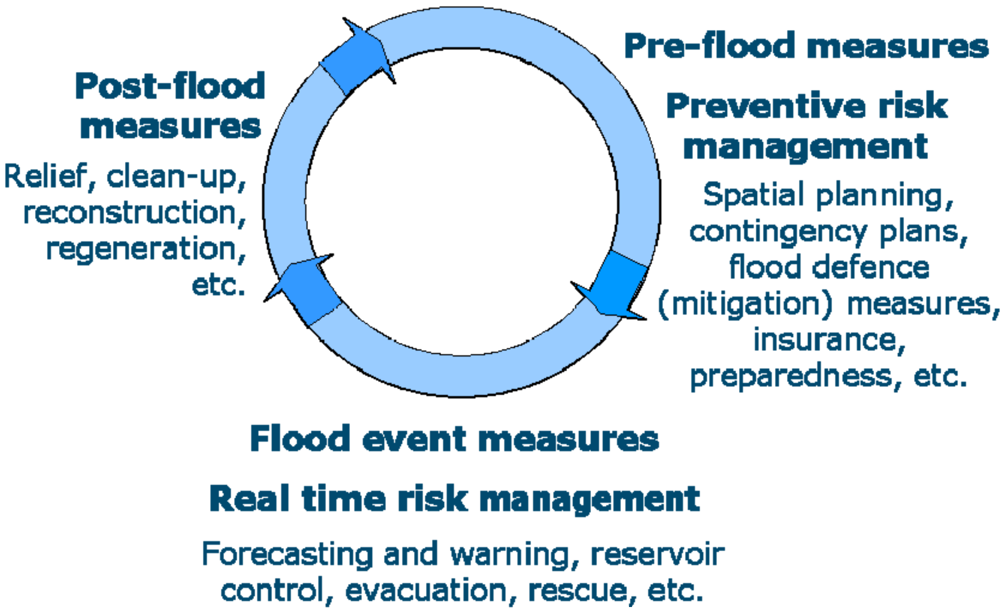

Figure 14 The flood risk management cycle (source HR Wallingford)

Institutional organisation and arrangements

The involvement of the public, politicians and professionals is essential in working out the sustainable development and management of river basins.

The mitigation of flood risks needs to be approached in practice on several fronts, with appropriate institutional arrangements made to deliver the agreed standard of service to the community at risk. These institutional arrangements differ according to national legislation and public tolerance of flood risks. Some of the differences in approach have been described, (Empson & Chapman 1996; Gendreau & Gillard 1997; Holst 1997; Jorissen 1997; Klaassen & Cappendijk 1997; Klijn et al. 2008).

To deliver this holistic flood management in practice requires the collaboration of professionals in several disciplines. For example, collaboration is required between meteorologists and hydrologists to improve flood forecasting and between engineers, planners and ecologists for the design of flood defences. In most developing and industrialised countries these professionals are engaged predominately in the public sector, since river basin regulation and management is usually the function of national or local government departments, agencies and authorities.

Long-term flood risk management

Traditionally a major aspect of flood mitigation has been the provision of structural flood defences, embankments, storage reservoirs, relief channels, etc. These can have substantial impacts on the riverine environment and ecology and the trend of national legislation has been to require detailed impact assessments and environmental statements to support the promotion of projects. This requirement drives the need for multidisciplinary working on the design of the flood alleviation schemes. An example of this is the implementation of the flood alleviation works on the lower river Thames and its tributaries (Gardiner 1998).

However, many major structural flood defence projects have been completed, particularly on lowland rivers and the recognition that future flood defence must be sustainable will influence the choice of measures implemented to further mitigate flood risk. It can be argued that a cycle of raising flood embankments and allowing unrestricted increase in the vulnerability to potential flood damage on the flood plain is not sustainable.

Kundzewicz identifies in his discussion of “Towards sustainable development of water resources” (Kundzewicz 1998), that the approach of living with floods is more sustainable than the historic approach of combating floods. He concludes that flood protection by catchment management, accommodating floods in flood plains and polders, flood proof construction and insurance measures deserve careful consideration. These are mostly non-structural approaches to flood risk management and so the prominence of non-structural measures is increasing as part of the sustainable management of rivers.

Non-structural measures mainly include:
- spatial planning policy with a presumption against development or encroachment of economic activities onto flood plains
- building regulations to control the additional runoff from any green-field development in the catchment outside the flood plain
- regulation of increases in vulnerability to flooding and of flood plain use
- provision of effective warning systems with emergency response plans
- insurance against flood losses
- public education in flood risk and the encouragement of personal measures to reduce flood losses.

Flood protection infrastructure

Channel capacity

At first sight increasing channel sizes is an obvious way to minimise the risk of local flooding. However, the subject has to be approached with care because man-made changes to natural river channels can have morphological consequences. A natural river channel develops an equilibrium shape and size dependent upon the flows it experiences, the nature and quantity of the sediment which passes and the characteristics of the river valley, its slope in particular.

In the upper reaches of any catchment, river channels tend to be wide and shallow. This is because the longitudinal slopes tend to be high and the sediments are coarse. Further down the catchment, river width-to-depth aspect ratios change and rivers tend to be deeper for a given width. This is because longitudinal slopes reduce, sediments become finer and flows increase. In the light of this natural behaviour of river channels it is unwise to make major changes to channel capacity under any circumstances and proposed changes of any significance should be undertaken with caution.

In rural areas, where rivers are more likely to be in their natural state, there is rarely a demand to increase channel capacity because the flooding of adjacent land areas has relatively few disadvantages and may indeed be of value to agriculture. In urban areas the situation is very different. The infrastructure adjacent to the river is often of high commercial value and this enhances the benefit/cost ratio of any proposed flood protection works. There is often little scope for increasing river widths and increased channel capacity can only be achieved by raising walls along the banks or by deepening the channel by dredging. Of the two approaches, raising walls is least likely to induce morphological change but it does increase flood levels, often well above adjacent ground levels. The overtopping of floodwalls in urban areas can have serious consequences both in terms of damage and loss of life.

Deepening channels by dredging can be effective in the short term but bed levels will tend to revert to their undredged state in the long-term due to siltation. There can therefore be a long-term maintenance commitment for flood protection schemes involving channels which are artificially dredged below their natural bed levels.

Embankments

Flood embankments are used in both the river and coastal environment.

In the river environment, embankments may be aligned along rivers where they attempt to contain flood flows within the channel. Under these circumstances they can be subjected to major erosive forces and can have an adverse effect on flood levels upstream. Where possible, flood embankments should be set back from the bank line to mitigate both of these effects.

In the coastal environment, earth embankments form a relatively economical way of protecting low-lying areas. In many cases they are set back from the coastline to minimise the risk of wave attack. However, failure during extreme events can have devastating consequences as experienced, for example, on the east coast of the UK and in Holland during the 1953 tidal surge in the North Sea.

Where coastal towns exhibit development up to the shoreline it is often necessary to provide hard protection in the form of sea walls. These can be expensive to build and maintain but the cost of failure is also high in terms of the damage which can be sustained by the adjacent infrastructure.

All coastal defence works have a knock on effect on the adjacent coastline. Protecting one area can cause serious erosion or accretion further along the coast.

Figure 15 Coastal embankment, Hartlepool, United Kingdom (source HR Wallingford)

Coastal embankments are used to protect low-lying coastal areas from inundation. Here the embankment at Hartlepool is being attacked and overtopped during high tidal levels combined with storm wave conditions.

Diversion channels and structures

One method of providing flood protection is to divert a proportion of the floodwaters around a vulnerable area. This method often applies in urban areas where man-made infrastructure has encroached upon the watercourse and the cost of reinstating an adequate flood path is prohibitive.

A structure is normally introduced at the head of the diversion channel so that flows can be controlled. This ensures that flows can be maintained within the main watercourse until its safe capacity has been reached and subsequent increases in flow can then be taken by the diversion channel. Operation along these lines helps to maintain the balance between flows and sediments in the main channel and minimises the risk of morphological change which can cause a reduction in channel capacity in the long-term.

Figure 16 Maidenhead, River Thames, United Kingdom

The flood protection scheme for Maidenhead on the river Thames takes the form of a regulated diversion channel, given the name "the Jubilee river", which takes around 40 per cent of the design flood event.

Storage reservoirs

Storage reservoirs are capable of reducing flows further down the catchment. The effectiveness of reservoirs depends on their size, the way they are operated, the characteristics of inflows and the nature of the catchment downstream.

Most storage reservoirs have controllable outlets. These take the form of gated ducts at low levels and/or high level spillways which ideally are also gated. These outlets provide flexibility in the way flows to the downstream reach are regulated.

Figure 17 Three Gorges Dam, Yangtze River, China

The Three Gorges Dam provides flood control, power generation and improved navigation. The initial flood storage at top water level was 22 cubic kilometres but this will fall in the long-term due to siltation.

Polders and compartmentalisation

Polders are most commonly found, though not exclusively so, in river deltas, former fen lands and coastal areas.

A polder is a low-lying tract of land enclosed by embankments, often referred to as dikes. They form artificial lakes which are connected with the external water environment through man-made gated structures. These structures are either manually operated or are automated according to an agreed set of operating rules.

There are three types of polder:
- land reclaimed from a body of water, such as a lake or the sea bed
- flood plains separated from the sea or river by a dike
- marshes separated from the surrounding water by a dike.

The ground level in drained marshes subsides over time and thus all polders tend to be below the surrounding water level some or all of the time.

Water enters low-lying polders through seepage or rainfall as a matter of course. This usually means that the polders have an excess of water which needs to be regularly pumped out or drained by opening sluices at low tide. During major flood events water can be fed into the polders and they act as off-line storage. This helps to reduce flood levels in the surrounding area.

The efficiency of polders in alleviating flooding depends on the storage volume available and the capacity of the gated structures which allow water into them, together with the magnitude and duration of the flood event. Thus, under normal circumstances, water levels in polders are kept as low as is practical.

Polders are at risk from flooding at all times and care must be taken to protect the surrounding dikes. Dikes are mostly built using locally available materials and each has its own risk factor. Sand is prone to collapse due to oversaturation by water, while dry peat is lighter than water, making the barrier potentially unstable in very dry seasons. There are also dangers from wildlife, particularly burrowing animals.

In some areas of the world interconnecting polders are constructed and this arrangement is know as compartmentalisation. It allows more flexibility in the control of major flood events. Large areas of Bangladesh have arrangements of this type.

Barriers and barrages

Barriers and barrages are man-made structures which are found in large rivers and estuaries. In large rivers they can be used to hold back flood flows to some extent but their effectiveness is limited by the storage available in the upstream reach before unacceptable water levels are reached.

In estuaries tidal barriers can be very effective in restricting upstream water levels during exceptionally high tides on the seaward side. The barrier is closed during the rising tide and opened again once the danger period is over. The exact time of operation of the barrier depends to some extent on the capacity of the upstream reach to temporarily store incoming fluvial flows. Hence operators of barrages need to take into account forecasts of both tidal levels and fluvial flows.

Water levels on the seaward side of a barrier are marginally higher than would otherwise be the case but the advantages upstream far outweigh the disadvantages downstream.

Figure 18 Thames Barrier, Greenwich, United Kingdom

The Thames Barrier is the world's second largest movable flood barrier after the Oosterscheldekering in the Netherlands. It is located downstream of central London and its purpose is to protect the city from flooding during exceptionally high tides.

Asset management

Asset management describes the practice of an organisation, particularly one responsible for public infrastructure, of recording the location, condition and maintenance record of the assets under their ownership or management. Thus an important component of flood risk management is the assessment of the condition of flood defence infrastructure in order to prioritise maintenance activities. Flood defence assets include raised embankments, river channels, pumping stations, storage reservoirs, etc. Several European countries undertake systematic asset management of flood defences (Jorissen 1997; Flikweert & Simm 2008). Good practice developed in the UK now involves a systematic inspection programme to record the condition of all the structural elements of flood defence schemes, with condition grades ranging from "very good" representing as constructed to "poor" which represents no effective function (Anonymous 2006). These conditions for the scheme as a whole, and more detailed analysis for each component, can provide an estimate of the probability of failure of the scheme in a flood event.

Preparedness

Preparedness is the ability to ensure effective response to the impact of flooding. It includes issuing timely and effective early warnings and the temporary evacuation of people and their possessions from threatened locations (Gouldby & Samuels 2009). Preparedness is an essential component of flood risk management with much of the activity undertaken during the quiescent, pre-flood phase of the flood risk management cycle. Preparedness requires active engagement with, and participation of, the community that may be affected by the flood. Public response can be made more effective by providing information on what to do in an emergency and through thorough contingency planning and practice. This involves a partnership between public authorities and the community networks which are involved in responding to flood events.

The means for preparedness will depend upon the social and cultural setting of the population at risk of flooding. In Mozambique, for example, a programme of sustainable flood risk management strategies included the production of educational tools to reduce the vulnerability of rural communities, (Lumbroso et al. 2008). The tools, which were developed in partnership with local stakeholders, included a source book on sustainable flood risk management strategies, a series of posters, a manual and a card game aimed at improving schoolchildren’s flood preparedness.

Flood insurance

Insurance against flooding presents a particular challenge, because any financial compensation for those who suffer flood damage, to cover rehabilitation costs, rests to some extent on the community at large. Those who seek flood insurance may be those who are exposed to a high risk of flooding whereas those in low risk areas challenge the notion that a flood risk premium should be imposed across the board (Kron 2009).

Resolution of this dilemma can only be achieved by increasing the knowledge and awareness of the flood risk in specific locations and by establishing the rehabilitation costs of various types of infrastructure which might be subject to flood damage. The insurance industry can then establish justifiable insurance premiums for specific degrees of flood risk and can impose conditions on the holder of insurance in the form of precautionary measures which must be taken to reduce exposure to risk.

The review of the summer 2007 floods in the UK, (Pitt 2008), made two specific recommendations relating to flood insurance in the UK:

- in flood risk areas, insurance notices should include information on flood risk and the simple steps which can be taken to mitigate the effects

- the insurance industry should develop and implement industry guidance for flooding events, covering reasonable expectations of the performance of insurers and reasonable precautions to be taken by customers.

Internationally, there is a diversity of approach to flood insurance, from none available in the Netherlands, a federally organised National Flood Insurance Program in the US to near universal open market availability in the UK (Botzen & van den Bergh 2008).

Flood event management

Even when a flood is imminent and certain to occur, the flood risk can still be managed through effective warning and emergency response during the event. Thus in most countries some form of flood forecasting operates, at least for the major rivers, to provide early information on a developing emergency and for public warnings to be given. Good flood forecasts are a prerequisite for effective flood warning but it is important to recognise the difference between flood forecasting and flood warning.

Flood forecasting

Flood forecasting covers the prediction of the nature and extent of a flooding hazard at some time in the future. Many scientific and technological advances have improved the quality and timeliness of flood forecasts.

Flood forecasting depends on the scale of the catchment and its response during flood events. In large catchments, flood forecasting can be achieved through observation of upstream river conditions and a flood routing model. For smaller catchments, rainfall-runoff modelling from recorded rainfall suffices, but in the catchments with the shortest timescale of response it is necessary to base forecasts on remotely sensed rainfall or forecasts of rainfall over the succeeding hours.

As the scale of the river basin decreases, flash floods become more likely as the time decreases between the occurrence of the most intense rainfall and the arrival of the flood. In such cases, flood forecasting and warning become the most important means of flood risk management. Lead-time is a critical issue in delivering an effective flood warning service and for catchments prone to flash flooding the science of radar hydrology has led to significant improvements in operational forecasting since the 1970's. Weather radar systems are used to track the movement of storms and the intensity of the rainfall. The radar observations are then closely coupled to meteorological models to provide highly detailed rainfall forecasts over a time horizon of a few hours.

Flood forecasting systems couple rainfall to computational hydrological and hydraulic models of the river basin to simulate the development of the flood. The predicted and observed water levels may be compared at regular intervals to optimise the performance of the forecasting methods during the event.

Flood warning

Flood warning deals with the institutional and public interface aspects of flood risk management during an event. In the early phases of a flood, warnings may only be alerts to the relevant public bodies and major industries that some flooding may occur. The European Flood Alert System (de Roo et al. 2003) provides some level of warning to national authorities with up to 10 or 14 days lead time in major river basins. This degree of early alert may enable national forecasting, warning and response services to prepare for a potential major incident through the mobilisation of staff, the reduction in level of flood storage reservoirs and checks that emergency equipment is in the correct location and is functional.

When more definitive and localised flood forecasts are available, possibly 6 to 48 hours ahead depending upon the basin size, the relevant authorities use the forecasts to provide appropriate information to those at risk.

Many factors influence the effectiveness of the flood warning, some of which are given in Table 7.

Table 7 Steps in achieving a response to a flood forecast and warning

Step	Issue
Awareness of a warning	Is the warning received before flooding occurs?
Availability to respond	Can the property owner reach the property to take action?
Ability to respond	Is the owner physically capable of mitigating flood damage?
Effectiveness of response	Does the owner know what to do and act effectively?

There is a need to present the warning information in a manner that can be readily understood by the intended recipients and is specific to the locality at risk. The full benefits of advances in knowledge in the science and technology of flood forecasting can only be achieved in combination with appropriate institutional and social systems to translate the forecast into actions which reduce and mitigate the flood impacts (Molinari & Handmer 2011). Thus the implementation of a flood forecasting system must be accompanied by:

- local plans to disseminate warnings
- identification of the areas at risk through flood mapping (Osti et al. 2009)
- public awareness of the extent of flood hazards and risks, the type of flood warning which will be issued and the actions to take on receipt of a warning
- means to issue general broadcast warnings and specific alert warnings to identified communities.

Disaster management

The management of a flood disaster will involve the mobilisation of resources from outside the area affected. External assistance in the management of a disaster is not new. The account of the response to the 1952 flash flood in Lynmouth in the UK (Delderfield 1953) describes the national scale of the response effort through the use of the resources of the military and civil authorities. The flooding of New Orleans from hurricane Katrina in 2005 led to a statewide emergency and a federal scale of response in the US. In less developed countries, disaster management may involve a partnership of international relief agencies coordinated through the national or regional government for the area affected. This occurred in the 2010 flood disaster in the Indus valley in Pakistan.

Review

The final step in the flood risk management cycle is to undertake a review of the performance and effectiveness of the relevant authorities in the flood. The importance of the review process is to identify lessons to be learned so that more effective measures may be taken to reduce the overall risk in the future. The review of the summer 2007 flooding in the UK (Pitt 2008) is an example of a wide ranging review of a serious event which causes disruption to the normal life of many communities through the loss of public water supply, failure of power systems and evacuation of residential and commercial buildings. The Pitt review produced 92 recommendations for change. These have been incorporated into new legislation through the Flood and Water Management Act (2010)) and have led to changes in responsibilities for the Environment Agency and Local Authorities.

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