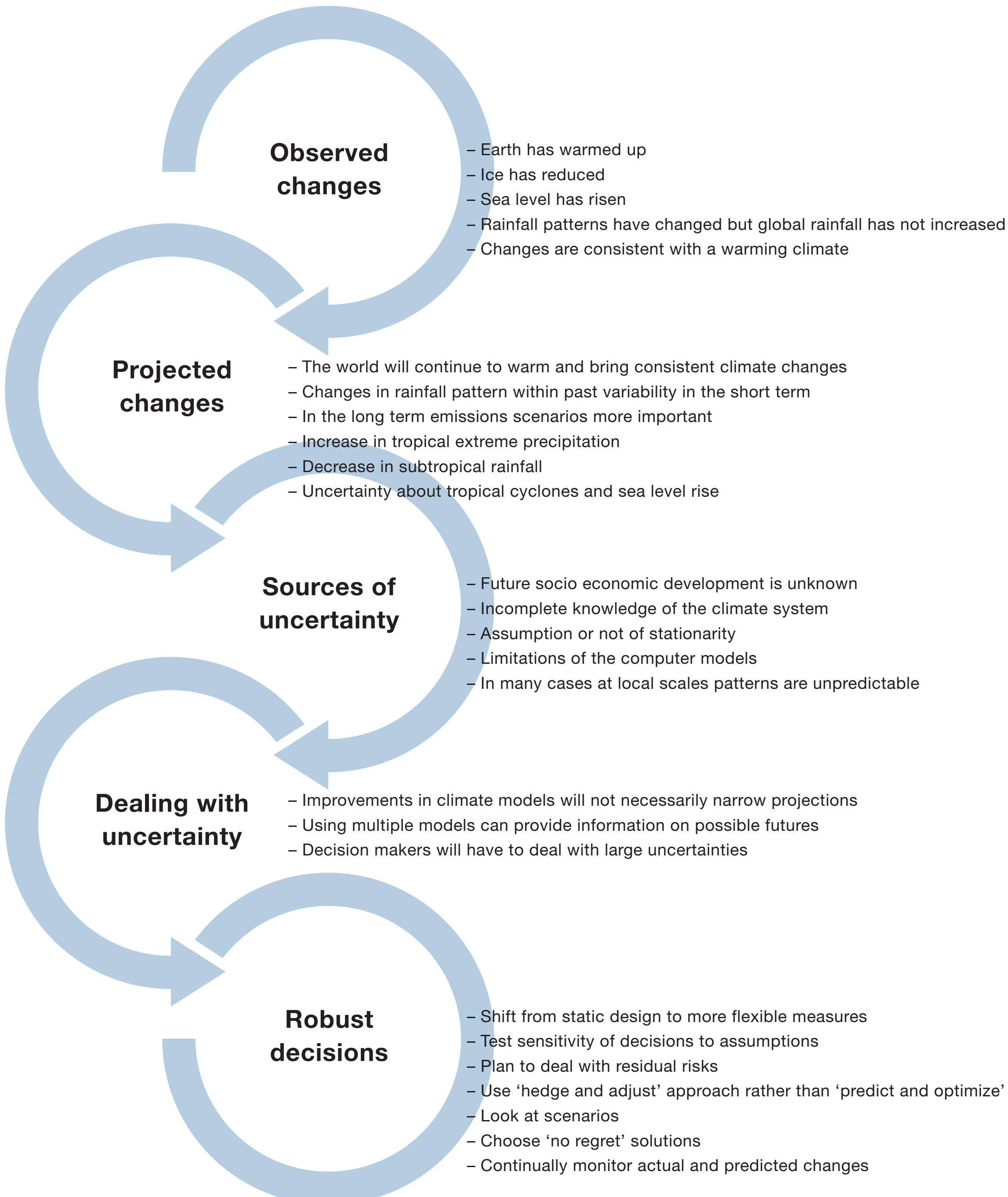

Figure 1.2 Making robust decisions in an era of climate change

Case Study 1.8: Mexico City's response to climate change and variability

Greater Mexico City, with a population of around 19.5 million, is one of the largest and most densely populated urban areas in the world. Over the past decades, the metropolitan area has experienced an increased incidence of flooding. Annual rainfall increased from 600 millimeters to over 900 millimeters through the 20th Century, while the annual incidence of flash flooding due to heavy rainfall increased from one to two annual flood events to six to seven flood events. It is expected that the incidence of flash flooding will continue to rise in the future due to the increased frequency of heavy precipitation associated with climate change and variability.

Flood impacts to Mexico City have also intensified mainly due to the way in which urban growth and spatial expansion are taking place. People living in informal settlements are particularly vulnerable, since they are often located in poorly or unplanned areas prone to flooding and landslides.

The municipal government of Mexico City recognized in recent years that climate change poses a serious threat to people and the economy and developed a 'Program of Climate Change Adaptation Measures' under a broader climate action program. This adaptation program, which is intended to become operational by 2012, identifies specific activities that are required in order to reduce the risks and the adverse effects of climate change and variability.

The first step of the program is the identification of primary threats to the city and a vulnerability analysis, followed by the integration of an adaptation perspective into existing government plans. The actual measures that will be then implemented have been categorized into two groups. The first group includes a hydro-meteorological monitoring and forecasting system and micro-basin management, such as the protection and restoration of urban ravines. The second group includes projects such as soil and water conservation projects and green roof schemes.

Both groups of measures selected include flexible and no regret measures, for example early warning systems and green infrastructure projects. Such measures are less sensitive to future flood risk and are relatively low in cost to set up. Although changes may be necessary in the future as risks change, flexible solutions allow for those changes without major reinvestment or the reversing of earlier actions.

Sources: Ibarrarán 2011; Martinez et al. 2008.

1.7. Technical Annexes

1.7.1. Types of flood models

Flood models can be categorized into several types depending upon their data requirement, level of complexity of the underlying equation, requirement of data for modeling, and the resolution.

Two important distinctions between models relate to the spatial aspects and input requirements. Models can be distinguished based on their spatial aspect of field characteristics:

- One dimensional (1D) models are simplified models which characterize the terrain through a series of cross sections and calculate the aspects like water depth and flow velocity towards the direction of flow. These models are well suited for areas where the direction of flow is well defined. Examples of such kind of model are the Beach profile model, HEC-RAS, LISS-FLOOD, and HYDROF.
- Two dimensional (2D) models calculate the flow non-parallel to the main flow i.e., they calculate the flow in both spatial dimensions with conditional uniformity. They are useful for modeling areas of complex topography such as wider floodplains or broad estuaries but require high quality data and long computation time. Examples of 2D model are TELEMAC 2D, SOBEK 1D2D, Delft 3D etc.
- Three dimension (3D) models are those where all the three components of velocity are considered. They are more complicated and thereby confined to modeling smaller areas. Some examples of 3D models are FINEL 3D, CFX, FLUENT, PHOENIX.

Based on inputs, flood models can be distributed into lumped models, distributed models and hydraulic models:

- Lumped models deal with the watershed as a single unit and the calculations are based on spatial average process. Semi-distributed models are also lumped models where the watershed is subdivided in order to model some of the physical parameters.
- Distributed models use distributed data like precipitation, infiltration, interception, interflow, infiltration, and base flow for forecasting purposes. This kind of model demands more data and knowledge than the lumped models.
- Hydraulic models use standard unsteady and non-uniform equations and are useful for measurement of flood wave travel time and attenuation.

Further classification of flood models is based on the implementation of techniques or methods; for example, linear models and non-linear models, finite element, finite difference and finite volume models, coupled models and nested models. The complexity of models is also reflected in their descriptions as first, second or third generation.

Additionally, there are two different approaches used in modeling flood events depending upon the user specific needs: probabilistic forecasts and runoff routing. In the probabilistic approach, statistical distribution is used to determine the uncertainty in model inputs. This method is gaining popularity because of its advantages of provision of probability of occurrence of flooding, including the level of uncertainty involved, thus aiding decision making. A rainfall–runoff approach provides complete hydrographs of the basin, by dividing it into sub-divisions and run offs routed from excess rainfall within each one. It is also advantageous for spatial distribution of rainfall over larger areas and, as a result, is helpful in prediction for larger basins.

For coastal flooding, erosion models are useful for estimating beach erosion to over wash and then breaching from the impact of waves. The most popular empirical model is that developed by Vellinga in the 1980s (FLOODsite 2008); this has been used in coasts of different morphology and characteristics and, although the original did not include this parameter, it has recently been modified to incorporate wave period (FLOODsite 2008). Other models include Komar et al. (1999, 2001), Kreibel and Dean (1993) and the Sheach Model (Larson et al. 2004), the latter having a wave propagation module to estimate cross shore transport in different zones. A detailed process based model to simulate breaching is TIMOR3 which was coupled with SWAN model to simulate sediment transport and bottom evolution (Witting et al. 2005). Attempts to develop a comprehensive erosion model are still ongoing.

Flood hazard simulation models are generally expensive to buy and require expert knowledge to use to get appropriate outputs. It is important for any flood manager to understand the importance of adopting an appropriate model based on the information needs for planned risk reduction and availability of resources. Table 1.2 earlier in this chapter describes the strengths and weaknesses of some common models. However, it should be kept in mind that not all developing countries can afford such expensive models for flood simulation. It is therefore important to have knowledge of the alternatives available in the form of freely available simulation software, which is discussed below in Section 1.7.3.

1.7.2. Flood hazard maps

Asia

An appraisal by the International Centre for Water Hazard and Risk Assessment reveals the present situation of flood hazard mapping in participant Asian countries (ICHARM 2010). It indicates that Bangladesh has large scale and medium scale inundation maps for the entire country up to district level and for the city of Dhaka. They have simulations up to 25-50 year return periods and are only used for flood forecasting and administrative purposes. These maps are not available to the public. Malaysia has flood hazard maps for the entire country up to a return period of 100 years for urban areas and 25 years for rural areas; updating of hazard maps of different catchments is in progress. Indonesia (for Jakarta) has flood maps for 1, 2, 5, 10, 25, 50 and 100 year return periods with inclusion of design structures, for example canals and rivers for the 100 year return period and ponds, macro and micro drains for 25, 10 and 5 year return period respectively.

Many countries have started involving the local people in community flood hazard assessment. In China, flood hazard has been simulated for 50-100 years for selected cities, reservoirs and embankment protection areas. The Philippines has flood hazard maps for the entire country and some of its most important cities for a return period of 25 years, while Thailand has them for 10, 20 and 50 years, taking into account the design structures for 500, 100, 50 and 25 year return periods. In India, flood hazard maps (known as 'Flood Atlas') are generated by the Central Water Commission (CWC); work is in progress on mapping flood-prone areas by organizations like the Building Materials and Technology Promotions Council (BMTPC) and the National Atlas and Thematic Mapping Organization (NATMO). The Indian Meteorological Department has also compiled statistics on values of probable maximum precipitation over the country, considering point rainfall data over a period of 24 hours, which is an important input for probability analysis and potential flood hazard assessment.

Europe

Flood hazard maps in Europe are generally available to the public, but their distribution and availability to the public domain varies by country. Flood maps in the UK are published by the Environment Agency, SEPA (for Scotland) and the Rivers Agency (for Northern Ireland); these illustrate flooding from rivers for a return period of 100 years, for coastal flooding 200 years and also provide an extent for an extreme 1000 year event. In Finland, flood maps are available from a scale of 1:20000 to 1:25000 for various return periods. In Germany, flood maps are produced separately depending on the end user, for example, for the general public the scale is 1:5000 with limited information but for research organizations and authorities the scale is much higher (information up to individual plot level can be obtained). In Hungary, flood maps have not been updated since 1972. In the Netherlands flood maps are available for different return periods to the public and are monitored and updated on a regular basis. In Bulgaria, maps of 1:50000 scales are available to the public; flood hazard maps are prepared on a hierarchical basis, from municipal level to the district level, then river basin level and finally at national level. Estonian flood hazard maps are available from the Meteorological and Hydrological Institute; and in Poland, they can be accessed at the Regional Board of Water Management and State Fire Service Head Quarters in scales of 1:25000 to 1:100000.

The Americas

In USA, the authority responsible for generation and distribution of flood maps is FEMA. Flood maps are available based on high, medium and low hazard zones and probability of occurrence (100 year, 500 year) for different locations at scales of 1:12,000, 1:6,000 and 1:24,000. There is also a provision of real time hazard mapping in some highly hazard prone areas. In Brazil the Agencia Nacional de Aguas is responsible for hazard mapping.

In the Caribbean region, flood hazard assessments are generally prepared by the national governments. In Belize, flood hazard assessments have been carried out since 1998-99, while the Government of Jamaica has undertaken a major flood hazard mapping program in the major river basins across the island. Mapping of inland flooding was completed by Antigua, Barbuda, St.Kitts and Nevis and they are available to the general public. The US Virgin Islands (USVI) developed a territorial flood hazard mitigation plan for remapping old archives. In Barbados, St. Vincent, Grenadines, Trinidad and Tobago, the Caribbean Disaster Emergency Management Agency (CDEMA) supported by the Japanese Government has undertaken pilot projects for mapping locational specific flood risks.

Africa

The hazard mapping situation in Africa appears to be the least advanced. There are few countries which have prepared hazard maps and those that exist are usually not available for public access. The Regional Centre for Mapping for

Resource Development in Nairobi, Kenya is responsible for mapping in the eastern part of Africa. Information is, however, available from the Dartmouth Flood Observatory in the US, which maintains a comprehensive database and archived maps of some of the major floods at different scales in different parts of the world including several countries in Africa (namely Zimbabwe, Mozambique, Malawi, Kenya, Uganda, Burkina Faso, Mali, Niger, Nigeria, Ivory Coast, Ghana, Togo, Benin and Guinea, Chad, Sudan, Ethiopia, Somalia, Tanzania, and Uganda). The observatory has a comprehensive archive of flood maps of different countries from other continents, which are freely available to the public. The list of maps available in the archive can be found here:

http://floodobservatory.colorado.edu/Archives/MapIndex.htm.

Data requirements for flood hazard mapping include:

- Discharge data for determination of peak discharge for probability assessment measures from different gauging stations
- Digital elevation model for estimation of elevation data
- Human-made structures and terrain, for example roads, buildings, bridges, embankments, dikes, other relevant structures to be incorporated within the DTM to generate digital surface model or incorporated separately to the model for analysis purpose
- Meteorological data: temperature, rainfall, snowmelt, wind speed
- Paleoflood and historical data obtained from geological, geomorphologic and botanical evidence of past flood events
- Topographic data for spatial estimation of hazard extent.

1.7.3. Tools for modeling and visualization

Most of the models and software used for flood hazard assessment are quite expensive to buy and are not freely available to public. Due to their high price they are an impractical consideration for many developing nations. High quality open source software, which will be able to serve the same purpose as these highly sophisticated models to does exist and can provide a general idea of the areas under threat.

Some of the open source software packages freely available for analysis and visualization purposes are as follows:

- A flow map designed by Utrecht University in the Netherlands is specifically designed to display flow data and works under Windows platform.
- GRASS is the most popular and well known open source software application which has raster and vector processing systems with data management and spatial modeling system. It works with Windows, Macintosh, Linux, Sun-Solaris, HO-Ux platforms.
- gvSIG is a GIS software application written in Java and works in Windows, Macintosh and Linux platforms.
- ILWIS is a multi-functionality GIS and remote sensing software which has the capacity of model building. Regular updates are available for this software.
- Quantum GIS is a GIS software which works with Windows, Macintosh, Linux and Unix
- SPRING is a GIS and remote sensing image processing software with an object oriented model facility. It has the capacity of working with Windows, Linux, Unix and Macintosh.
- uDig GIS is a desktop application which allows viewing of local shape files and also remote editing spatial database geometries.
- KOSMO is a desktop application which provides a graphic user interface with applications of spatial database editing and analysis functions.
- Interactive visualization tools:
- Showing sea level rise: http://globalfloodmap.org/South_Africa.
- Global Archive map of extreme flood events (1985-2002): http://floodobservatory.colorado.edu/Archives/GlobalArchiveMap.html.

Deltares, a leading research institute based in the Netherlands, has released specific modules of the Delft 3D model (FLOW, Morphology and Waves) as open source to bring experts all over the world together to share knowledge and expertise. It is a robust, stable, flexible and easy to use model which is internationally recognized; for more information see the following link: http://oss.deltares.nl/web/opendelft3d/home.

It must be borne in mind that uncertainty exists in every stage of hazard assessment, including data accumulation, model selection, input parameters, operational and manual handling of the model until the final output is obtained. Each element contributes to the uncertainty in accuracy of the final output, it is, therefore, necessary to consider the impact that uncertainty has on the output of a model and is essential to reduce this as much as possible.

1.7.4. Examples of flood forecasting and early warning systems

There are a several useful examples of such systems:

- DELFT-FEWS: one of the state of the art hydrological forecasting and warning systems developed by Deltares. This system is an integration of a number of sophisticated modules specialized in their individual capacities and the system is highly configurable and versatile. The system can be used as a standalone environment, or it can be used as a compliant client server application. Through its advanced modular system FEWS has managed to reduce the challenges like handling and integration of large datasets to a considerable extent. For further information see: http://www.deltares.nl/en/software/479962/delft-fews/479964?highlight=delft%20fews.
- Automated Local Evaluation in Real Time (ALERT) is the method used within the AUG member states to transmit data and information using remote sensors for warning against flash floods.http://www.sutron.com/project_solutions/Case_Studies_Individual.htm.
- Central America Flash Flood Guidance is an example of regional flash flood warning. The national Hydrologic Warning Council (NHWC) has member countries across North America and many parts around the world; it is also a major organization in data dissemination for early warning for flood events.
- The Mekong River Commission flood forecasting system, discussed above, has been operating since 1970. It is an integrated system which provides timely forecasting to its member countries. It consists of three main systems of data collection and transmission, forecast operation and information dissemination at both national and regional level. For more information see: http://www.mrcmekong.org/.
- The Southern African regional model for flood forecasting Stream Flow Model (SFM) has been applied after the Mozambique flood in 2000. The USGS along with Earth Resource Observation System (EROS) supports monitoring and modeling capacities of Southern African Countries.
- Regional Water Authority of Mozambique (ARA-Sul) is responsible for issuing flood warning and real time forecasting. The system is operational in Southern Africa with a mean area of 3,500 square kilometers. A simplified flood warning system, the Mozambique Flood Warning Project, is specially tailored to the needs of the local population. It also involves the local people and trains them to install, monitor and maintain the structures.
- Hydro Met Emergency Flood Recovery Project is used in Poland.
- Bhutan’s Glacial Lake Outburst Flood (GLOFs) Iridium Satellite Communications is used as the telemetry back-bone for Bhutan’s GLOF Early Warning Project.

- In the Toronto region of Canada, the Toronto and Region Conservation Authority (TRCA) flood forecasting and warning system is used; this is a scalable flood warning system including web-based data and video for nine watersheds.
- The Automatic Dam Data acquisition and alarm reporting system, is the Puerto Rican System to obtain, monitor and analyze, in real-time, critical safety parameters such as inflows, outflows, gate openings and lake elevations for 29 principal reservoirs
- Central Water Commission (CWC) in India provides the Turnkey Flood forecasting system across 14 states having 168 remote sites in six river basins. http://www.india-water.com/ffs/index.htm.

1.7.5. Downscaling Global Climate Model (GCM) information

Projections of climate change are generally obtained using GCMs whose spatial resolutions are typically of the order of a hundred kilometers. Different methods have been developed to generate climate change hazard information at spatial scales more relevant for adaptation planning. Following Wilby et al. (2009) a description of these follows, together with a summary of each approach's strengths and weaknesses.

1.7.5.1. Methods requiring limited resources

These approaches are modestly data dependent, place minimal demands on technical resources, and can be valuable for scoping assessments.

i) Sensitivity analysis: This requires a fully calibrated and validated model of the chosen system, for instance a model of coastal flood inundation in a given region. First the observed climate is fed into the model to establish the baseline conditions. Then, the observed climate is perturbed by fixed amounts to reflect arbitrary changes in precipitation for instance. A model simulation is performed for each change and any system response is measured against the baseline, providing a picture of the sensitivity to changes in the climate drivers.

Advantages: Easy to apply; requires no future climate change information; can indicate system thresholds.

Disadvantages: provides no insight into the likelihood or timing of different impacts; it cannot provide information about sequences of weather events that have not been recorded in the observations; perturbed time series might result not physically plausible; impacts model uncertainty is ignored.

ii) Change Factors: Provided that climate model information is available through GCM simulations, change factors between present and future climatology (typically long term averages for each calendar month) are calculated for the grid boxes overlying the region of interest. Change factors for temperature are computed as differences and for precipitation as proportional changes. These change factors are then added to the observed time series in the case of temperature (or multiplied by the observations in the case of precipitation) to generate perturbed climate time series.

Advantages: easy to apply (given availability of climate model data).

Disadvantages: perturbs only baseline mean and variance; ignores, for instance, changes in frequencies of rainfall and temporal sequencing of events; perturbed time series might result not be physically plausible or may lack consistency between different variables; it depends on the availability of GCM or Regional Climate Model (RCM) data for the location of interest.

iii) Climate analogues: analogue scenarios are constructed from paleo-data or more recent instrumental records that provide plausible representations of the climate of a region. Temporal analogues are taken from previous climate of the region; spatial analogues are taken from another region that has present conditions that could become the future climate of the Study site. The underlying assumption in constructing these analogues is that the geographic location between regions is similar and that the typical features of different latitudes (when using analogues from different zones) are not important.

Advantages: easy to apply; require no future climate change information; potentially reveals multi-sector impacts and vulnerability to past climate conditions or extreme events such as a flood or a drought.

Disadvantages: temporal analogues require that the climate forcing that led to extremes in the past is repeated in the future, however that is unlikely to happen if for instance human activities led to land use changes. Even if the same climate event recurs in the future, the impact will be different due to changing confounding factors such as changes in economy, infrastructure development or adaptation measures implemented during the interim.

iv) Trend extrapolation: extrapolating a trend over the next few years is an appealing option due to its simplicity. However, this assumes that recent trends will continue unchanged, and most importantly, that past records can provide robust information about trends. Even though this assumption might be correct for the slow changing components of the climate system (such as global sea level rise) at relatively short time scales, the trends are highly susceptible to false tendency due to data problems for instance, and their extrapolation ignores the possibility of abrupt changes in, for instance, climate circulation or rainfall patterns.

Advantages: easy to apply; uses recent patterns of climate variability and change.

Disadvantages: typically assume linear trend, trends are sensitive to the choice of records; it assumes that underlying climatology of a region is unchanged; needs high quality observational data; confounding factors can cause false trends.

1.7.5.2. Methods requiring modest resources

These methods are based on the use of different statistical approaches that in combination with climate model output generate projections of climate change.

i) Pattern scaling: this method is similar to the change factor approach; a spatial pattern of change for every grid box on the globe is derived using output from a GCM or RCM. These spatial patterns are then scaled using the global mean temperature change, simulated by a simple (and easy to run) climate model. This generates spatially resolved scenarios of climate change, for instance, different anthropogenic forcing, or different periods that have not been simulated by full GCMs. This approach relies on several major assumptions: that regional climate change patterns are constant between decades and only the magnitude of change varies; that the regional response depends linearly with global mean temperature change; and that the pattern of change can be scaled between different emission scenarios.

Advantages: modest computational resources only are required; allows analysis of GCM and emissions uncertainty; shows regional and transient patterns of climate change.

Disadvantages: relies on strong assumptions about the linearity of the climate response to different forcing; generated scenarios have coarse spatial resolution (same as GCM or RCM used to generate the patterns); fails to reproduce climate variability necessary to identify extremes.

ii) Weather generators: are models that replicate statistical attributes of meteorological station records (such as mean and variance) but do not reproduce actual sequences of observed events. In most cases a Markov model emulates transitions between wet and dry spells or dry-days, a probability distribution is used to optimally simulate daily rainfall totals, and secondary variables such as maximum and minimum temperatures, solar radiation and wind speed are obtained using multiple regression equations that link them to wet and dry-days. The use of weather generators to simulate projections of climate change assumes that statistical relationships valid under current climate will not be modified under climate change.

Advantages: modest computational demand provides daily or sub daily meteorological variables.

Disadvantages: needs high quality observational data for calibration and validation; assumes a climate change independent relationship between large-scale circulation patterns and local weather; scenarios are sensitive to choice of predictors and quality of GCM output; results are typically time slice rather than transient; it is limited to reproduce only time correlations for lags it has been trained to reproduce and can not simulate longer term temporal correlations.

iii) Empirical downscaling: in its simplest version consist of spatial interpolation of gridded GCM or RCM data to the required location (a particular place in a catchment for instance). More sophisticated approaches involve finding statistical relationships between large scale atmospheric variables (predictors) and local surface variables (predictands) at the location of interest. Different downscaling approaches can be distinguished by their predictor variables or by the form of the statistical model relating predictors to predictands.

Advantages: modest computational demand; provides transient daily variables, reflects local conditions; can provide scenarios for ‘exotic’ variables (such as urban heat island, or air quality).

Disadvantages: requires highly quality observational data for calibration and verification, assumes a constant relationship between large scale circulation patterns and local weather; projections are highly dependent on the choice of predictands and the GCM used to estimate the predictands in the future.

1.7.5.3. Methods requiring high intensity resources

These methods require a high degree of ongoing technical support and computing resource, but on the other hand they are the only methods that can produce in principle internally consistent climate simulations in response to different climate forcings. One is discussed below, as an example:

Dynamic downscaling: Regional Climate models (RCMs) are similar to GCMs but run at much higher resolution over a limited spatial domain (a continental region for instance). RCMs simulate climate variables dynamically at resolutions of 10-50km given that boundary conditions are provided at the limits of their spatial domain. Atmospheric fields such as surface pressure, wind temperature and vapor, simulated by the parent GCM are fed into the boundary of the RCM at every time step and different vertical and horizontal levels. The nesting of the RCM within the GCM is one way, so the behavior of the RCM does not influence the GCM. Therefore, the robustness of RCM simulations depends not only on the validity of the RCM physics, but also on the validity of the GCMs boundary information. For instance, gross errors in the RCM simulated precipitation can be caused by the parent GCM misplacing the storm track. The results are sensitive to the size of the RCM domain and grid spacing. In theory, the domain should be large enough to capture large scale atmospheric circulation, and the grid space small enough to resolve topographic, coastal and dynamical features such as tropical cyclones crucial to simulating local climate. In practice domain and grid spacing are limited by computational resources.

Advantages: maps regional climate scenarios at 20-50 kilometer resolution, reflects underlying land-surface controls and feedbacks at smaller scales; preserves relations between weather variables as simulated by the climate model; ensemble experiments are becoming available for uncertainty analysis.

Disadvantages: high computational and technical demand; the results are sensitive to the host GCM; requires high quality observational data for model verification; scenarios are typically time slice rather than transient; climate model uncertainties and sources of error are the same as for GCMs but compounded with the parent GCM uncertainties.

It is important to note that this approach cannot provide ‘magical fixes’ to possible limitations in the data being downscaled. If for instance GCM data is being downscaled using an RCM or a statistical downscaling technique to obtain information at the local catchment scale, the downscaled information will not be robust if the GCM data was not robust. In fact, the downscaling approach will only introduce one more source of uncertainty in the resulting output. In this case the generation of climate projections using downscaling techniques will almost certainly increase the level of uncertainty in the original GCM projections.

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Graham Leith and his son Kieran outside the flooded house of his mother Doreen Leith in Toll Bar village outside Doncaster, UK (2007). Source: Gideon Mendel

Chapter 2

Understanding Flood Impacts

Chapter 2. Understanding Flood Impacts

2.1. Introduction

Chapter Summary

This chapter translates the concept of flood hazard into flood risk. The following questions are addressed in order to assess the urgency and necessity of tackling flood risk before an event and to help in dealing with an actual flood:

What impact does flooding have on urban areas? Who and what are affected and for how long? What effect does urbanization have on flood risk? How can resources be targeted to protect those most vulnerable?

Key messages from this chapter are:

- Rapid urbanization severely challenges existing flood management infrastructure but also presents an opportunity to develop new settlements that incorporate integrated flood management at the outset.
- Direct impacts from major events represent the biggest risk to life and property, but indirect and long term effects and regular more minor flooding can erode other development goals.
- The poor and disadvantaged suffer the most from flood risk. Mapping risk and vulnerability assists in directing resources to protect them.

Flooding is one of the major natural hazards which disrupt the prosperity, safety and amenity of human settlements. The term flood refers to a flow of water over areas which are habitually dry. It covers a range of types of event, many of which can also include other sources of damage such as wind. Sources of floodwater can arise from the sea (in the forms of storm surge or coastal degradation), from glacial melt, snowmelt or rainfall (which can develop into riverine or flash flooding as the volume of water exceeds the capacity of watercourses), and from ground infiltration. Flooding can also occur as the result of failure of man-made water containment systems such as dams, reservoirs and pumping systems.

Excess water in and of itself is not a problem; rather, the impacts of flooding are felt when this water interacts with natural and human-made environments in a negative sense, causing damage, death and disruption. The experience of flooding for a rural agriculturalist and an urban slum dweller will be very different:

to the farmer the flood is a natural force to be harnessed or endured for the long-term benefits it may bring, but for the urban dweller flooding is, at best, a nuisance and at worst a disaster which destroys all possessions.

This chapter is concerned with the impacts of flooding in urban environments.

First, in Section 2.2, it describes the challenges posed by rapid urbanization and urban expansion, stressing the situation of informal settlement or slum areas, both in central city and peripheral locations, which are known to be particularly vulnerable to flood impacts. Case studies are used to throw light on the actual situation in the field.

Section 2.3 explains the direct impacts of flooding on primary receptors including people, the urban built environment, infrastructure, and family assets. Risks to life and health caused directly or indirectly by flood water are discussed, with flood-related injuries described in the pre-onset, onset and post-onset phases.

Damage to buildings and infrastructure is then examined, again detailing both direct and indirect damage. The characteristics of a flood are seen to be an important factor in determining the extent and nature of damage caused. Methods of construction, the use of construction materials and different forms of building are also shown to have implications for the severity of damage. Damage to infrastructure is shown to be a significant challenge to and inhibitor of post-event recovery.

The section goes on to provide an example of how to perform a damage assessment which makes uses of the Damage and Loss Assessment (DALA) methodology.

Section 2.4 provides a discussion of the other effects of flooding, including the impacts on the natural environment (such as erosion and landslides) and longer-term human and social impacts (including effects on demography and economic, and political and institutional impacts). The psychological and mental effects of flooding on people are also discussed.

The approach taken in this chapter is based on a commonly-accepted definition of flood risk: as a function of the flood hazard, of exposure to the flood hazard, and of the vulnerability of receptors to the flood hazard. It should be noted that exposed receptors may be vulnerable to the hazard or alternatively may be resilient to it. The final Section 2.5 describes the various options for assessment of risk and vulnerability, together with approaches to mapping, and includes discussion of the types and sources of data required. Categories of vulnerability are explained and the factors affecting their rate of exposure presented. The chapter ends with a detailed explanation of how to undertake a vulnerability assessment.

2.2. Urbanization, urban expansion and urban poverty

In the short-term, and for urban settlements in developing countries in particular, the factors affecting exposure and vulnerability to flooding are increasing rapidly, as urbanization – broadly defined as the transition from rural to largely urban societies – puts more people and more assets at risk. Rapidly growing informal settlement areas, often termed slums, in central city and peripheral suburban or peri-urban locations, are particularly vulnerable to flood impacts.

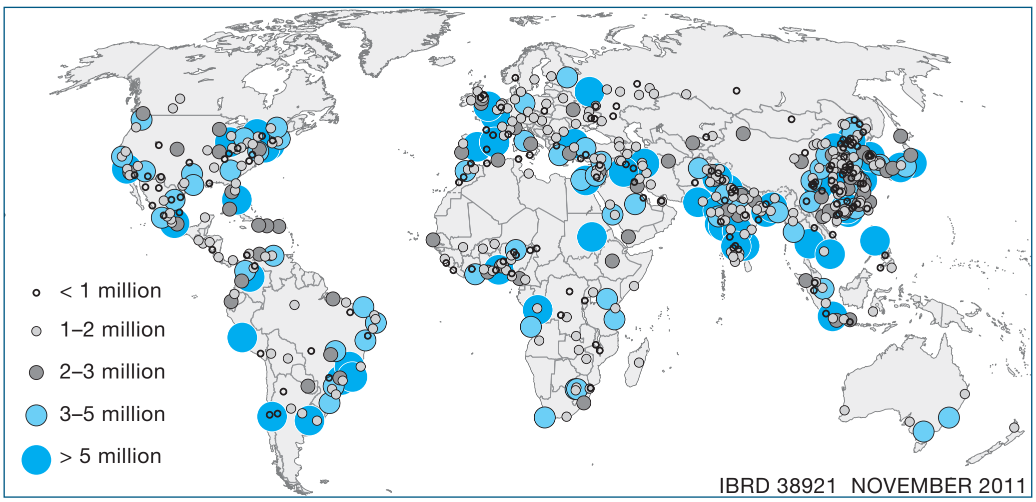

Figure 2.1: Urban agglomerations with more than 750,000 inhabitants in 2010.
Source: Based on Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2008 Revision and World Urbanization Prospects: The 2009 Revision.

2.2.1. Urbanization trends

In 2008 for the first time in human history, half of the world's population lived in urban areas, as illustrated in Figure 2.1 (UN-HABITAT 2008). It is estimated that by 2030 some 60 percent of the world's population will live in urban areas and by 2050 this will have risen to 70 percent (UN-HABITAT 2008; WDR 2010). In the developing world, some 95 percent of urban population growth takes place in low-quality, overcrowded housing or in informal settlements, with urbanization rates typically higher in small and medium-sized cities, although this varies from continent to continent (WDR 2010; WGCCD 2009; Parnell et al. 2007).

In East Asia, for example, most of the increase in urban population over the next 15 years is expected to be in towns and cities with fewer than one million inhabitants (Jha and Brecht 2011). In addition, a significant percentage of urban growth will be in peripheral areas adjoining existing major cities. However, it is important to understand that urban areas are not necessarily cities: Satterthwaite (2011: 1764-65) points out:

"Although it is common to see the comment that more than half the world's population lives in cities, this is not correct: they live in urban centers, a high proportion of which are small market towns or service centers that would not be considered to be cities."

2.2.2. Defining the 'urban'

Although the world is becoming more urban in nature, there is no commonly accepted definition of what is meant by the term 'urban'. Often, places with paved streets, street lighting, piped water, drainage and sanitation infrastructure, hospitals, schools, and other public institutions, are considered as urban areas. Urban centers, however, vary in size from a few thousand inhabitants to megacities with more than 10 million inhabitants. In addition, urban areas vary with regard to their spatial form, economic base, local resource availability, and local institutional structure. Typically, the conception of urban is now seen within the perspective of a rural-urban continuum spanning, in any given society, villages, small towns, secondary (or medium-sized) cities, metropolitan areas, and megacities. In addition, significant urbanized agglomerations are emerging, covering entire urban regions or urban corridors which encompass a range of urban centers of different sizes.

There are also significant regional differences: a town of a few thousand people in Africa is often considered to be an urban center, whilst in Asia urban areas tend to be agglomerations with far larger populations. There is even greater variation in the level and speed with which individual countries and individual cities within regions are expanding (Cohen 2004). For example, Latin America is more urbanized than Africa or Asia, and matches Europe or North America with current urbanization levels of around 70 percent. However, urbanization trends in Latin America are lower than in Asia and Africa, which are expected to experience relatively faster rates of urbanization over the coming decades. By 2030, Sub-Saharan Africa, which is the fastest-urbanizing world region, will have crossed the threshold to be a principally urban region. In the 20 years that follow, Africa's urban population will rise to 1.3 billion people.

2.2.3. Implications of urbanization and urban expansion for local environments and the flood hazard

Urban centers concentrate people, enterprises, infrastructures and public institutions, while at the same time relying for food, freshwater and other resources from areas outside of their boundaries (Satterthwaite 2011). Furthermore, urban areas are often located in hazard-prone locations such as low-elevation coastal zones, which are at risk from sea-level rise, or in other areas at risk from flooding and extreme weather events (OECD 2009; WDR 2010).

Urbanization is accompanied by increasingly larger-scale urban spatial expansion as cities and towns swell and grow outwards in order to accommodate population increases. Urban expansion alters the natural landscape, land uses and land cover, for example by changing water flows and increasing impermeable areas, thereby adding to the flood hazard problem (Satterthwaite 2011). High levels of urbanization in river flood plains and other areas of catchments might also change the frequency of occurrence of flooding. In the mid-1970s, when urbanization was just starting to accelerate, a study by Hollis (1975) showed that the occurrence of small floods might increase up to 10 times with rapid urbanization, whilst more severe floods, with return periods 100 years or over, might double in size if 30 percent of roads were paved. The changes in land use associated with urbanization affect soil conditions and the nature of run-off in an area. Increased development of impermeable surfaces leads to enhanced overland flow and reduced infiltration. It also affects the natural storage of water and causes modification of run–off streams (Wheater and Evans 2009).

Urban centers also change the local environment by reducing rainfall and increasing night-time temperatures. Urban micro-climates, especially urban heat islands caused by lack of vegetation, can modify the hydrology of an area. Heat islands create higher temperatures over cities: for example, during the summer heat wave of 2003 in the UK, differences of up to 10°C between city and rural temperatures were measured in the London area.

The ways in which the effects of urbanization combine with limited urban planning and inadequate maintenance of waterways to lead to increased vulnerability to flooding is illustrated in Case Study 2.1.

Case Study 2.1: Changing rainfall patterns and poor urban planning expose Lusaka to floods

Floods caused major disruption to Lusaka, Zambia in March 2010. As one account put it:

"Water rose above the window levels of many houses, strong currents carried away pieces of market stalls and boys hoisted fishing nets to catch whatever they could from the gullies where, not long before, they had walked to school."

March usually marks the end of the country's rainy season. But in 2010 the rains were more intense and longer than usual. Population pressures and the need for improved urban planning in Lusaka have increased people's vulnerability to floods: according to the country's Central Statistics Office, Lusaka's population has increased by 400,000 people since 2004, reaching at least 1.5 million currently. This trend, caused by in-place growth and rural-urban migration, is expected to continue. Population densities have also increased, particularly in peri-urban areas on the city's periphery, where they reach up to 1,450 persons per hectare according to the Lusaka City Council. Some 70 percent of inhabitants are under 30.

As 60 percent of Lusaka's residents live in dense, informal, unplanned settlements, the local population is particularly vulnerable to floods. Specifically, many houses have been built in areas not suitable for construction or which are highly vulnerable to flooding, particularly as drainage channels are often blocked by buildings or filled with waste.

It is also important to highlight the effect that floods have on human health. According to the Ministry of Health, in March 2010 564 cases of cholera were recorded in Zambia, with 30 deaths in Lusaka. This also had much to do with poor wastewater management and potable water boreholes being inappropriately designed or built.

The Ministry of Finance estimates that upgrading Lusaka's drainage system - not to mention improving wastewater management, treatment and disposal and improving access to safe and reliable drinking water - would be very costly.

However, in the 2011 national budget only US$33.2 million was allocated for water and sanitation projects in Zambia. As a result, Lusaka's problems are likely to continue to grow unless further investment is secured. Furthermore, given the level of ongoing urbanization, such investment needs to be allied with improved urban planning and management.

Source: Kambandu-Nkhoma (no date).

2.2.4. The urban poor

The concentration of people in urban areas increases their vulnerability to natural hazards and climate change impacts. Vulnerability to flooding is particularly increased where inappropriate, or inadequately maintained infrastructure, low-quality shelters, and lower resilience of the urban poor intertwine (World Bank 2008). The fact that rapid urban expansion typically takes place without following structured or agreed land use development plans and regulations makes conditions even more problematic. In addition, as the urban poor are often excluded from the formal economy, they lack access to adequate basic services and because they cannot afford housing through the market they are located in densely populated informal slum areas which may be vulnerable to flooding.

The houses of poor people in these most vulnerable informal settlement areas are typically constructed with materials and techniques that cannot resist extreme weather or natural disasters (Parry et al. 2009). Rapid urbanization in low-income and middle-income nations tends to take place in such relatively high-risk areas, thereby placing an increasing proportion of the economies and populations of those countries at risk (Bicknell et al. 2009).

Case study 2.2 presents an example of the complexity of the impacts of urban flooding on the urban poor.

Case Study 2.2: The dilemma of poverty and safety: The case of urban flooding in the Aboabo River Basin in Kumasi, Ghana

In the Kumasi Metropolitan Area (KMA), which is the second largest city in Ghana with a population of approximately 1.6 million, the Aboabo River Basin is home to various communities, namely the Anloga, Dichemso, Aboabo and Amakom. Flooding in the river basin affects life and property in many ways. In particular, urban flooding affects the built environment considerably, as many structures are impacted by the floods. In some instances, both completed and uncompleted buildings are abandoned as a result of what is now an annual phenomenon.

An interesting insight into the causes of flooding was provided by residents who live in the area in a recent survey conducted by academics from the city's Kwame Nkrumah University of Science and Technology (KNUST). According to survey respondents, the most important cause of flooding is improper garbage or refuse disposal. A large percentage of the residents indicated that the method for refuse disposal was an issue. They believed that it was a major cause of the flooding problem since drains and the river bed itself were both choked with refuse. The next important cause of flooding incidence is the lack of drains in the area.

According to the survey, 61 percent of all respondents continued to live in the area, despite enduring the phenomenon of flooding each year, because they could not afford the cost of moving to another place. Some 10 percent continued to stay on because of proximity to their places of work, or because they had businesses at the flood risk areas where they also lived. Another 19 percent remained for other reasons, such as having lived there all their lives, or because the land belonged to them or was their family home.

The above evidence validates the assumption that it is socio-economic factors which affect the motivation of urban populations to stay in flood-prone areas. Residents remain in these at risk locations because of a variety of reasons but seemingly it is the cost of moving which prevents them from relocating. The case highlights some of the social issues that have to be considered in developing robust flood risk management plans and strategies.

Source: Personal communication: Divine Odame Appiah, Lecturer, Environmental Resources Management, KNUST, Kumasi, Ghana

2.2.5. Urban challenges

The economies of urban centers vary from simple, small market towns to more complex, large cities and metropolitan regions serving local, regional, national and global markets. Cities are usually major economic centers hosting enterprises and industries that create most of the Gross World Product (GWP) (Kamal-Chaoui and Robert 2009; Bicknell et al. 2009). However, the benefits associated with urban centers are not unalloyed. This is mainly because of the existence of negative externalities, including environmental costs such as high carbon-intensities, as well as the high vulnerability to climate change and natural disasters such as floods (Corfee-Morlot et al. 2009).

In addition, urbanization is to an extent responsible for higher concentration of greenhouse gases (GHGs) in urban areas and cities, causing greater capital costs and environmental damage (Corfee-Morlot et al. 2009). Rapid urbanization also means that urban centers will need to invest in infrastructure services given the increase in the demand for these (Jha and Brecht 2011).

Urbanization and consequent increases in urban populations, accompanied by urban expansion, can result in declines in average densities, as built-up areas spread outwards. This can compound flood risk and weaken urban resilience to flooding. Even though some of this increase is the natural consequence of urban population growth, urban expansion, which is often referred to pejoratively as urban sprawl, can also be associated with inefficient land use and planning policies (World Bank 2008). However, the need for accommodating expanding urban populations does require the consumption of more land. Similarly, higher densities are not always or necessarily a panacea for alleviating urban flood risk, as they often are coupled to increases in non-permeable surfaces, the occupation of vulnerable terrains, and levels of congestion which can compromise or even overwhelm the operation of infrastructure services such as solid waste. Photo 2.1 illustrates the impact of flooding on an informal settlement.

Photo 2.1: Informal Settlement in Mexico City, Copyright: UN-HABITAT.

2.2.6. Opportunities

The unprecedented rate of global urbanization in cities and other urban areas implies that exposure and vulnerability is increasing, which will cause loss of life and property unless proactive measures are mainstreamed into urban planning processes (Jha and Brecht 2011). Cities themselves are often blamed for social inequalities, the inadequacy of city governments, authorities and institutions, and environmental degradation (UN-HABITAT 1996; Dodman 2009). Nevertheless it should be recognized that cities can contribute towards more sustainable development, if they are adequately planned, governed and managed. Rapid urbanization presents the opportunity to do things right first time, by integrating flood risk management concerns into new settlements as they develop. As Dodman (2009: 186) argues, many of the processes implicit in urbanization may have a beneficial effect on global environmental change, as economies of scale and proximity can provide cheaper infrastructure and services. In order for cities to take advantage of their potentials, however, good governance and urban planning are prerequisites.

The Working Group on Climate Change and Development (WGCCD 2009) suggests that urban authorities in developing countries need to deal with both outdated infrastructure and urban expansion if they want to increase resilience in the face of climate change. Moreover urbanization shifts the balance of prevention from individual measures to collective action (World Bank and United Nations 2010). As a consequence, to address the flood risk that cities and urban areas in low- and middle-income countries face, a coherent, locally-specific and integrated response to this environmental hazard and risk is needed.

2.3. Direct impacts on primary receptors

This section outlines the direct impacts of flooding on primary receptors including people, the urban built environment, infrastructure, and family assets. Risks to life and health caused directly or indirectly by flood water are discussed, with flood-related injuries described in the pre-onset, onset and post-onset phases.

2.3.1. People

Floods worldwide pose a range of threats to human life, health and well-being. In 2010, reported flood disasters killed over 8,000 people directly. While economic losses rise, direct deaths from flooding may be declining over time as measures to prevent flooding are employed, particularly in developed countries.

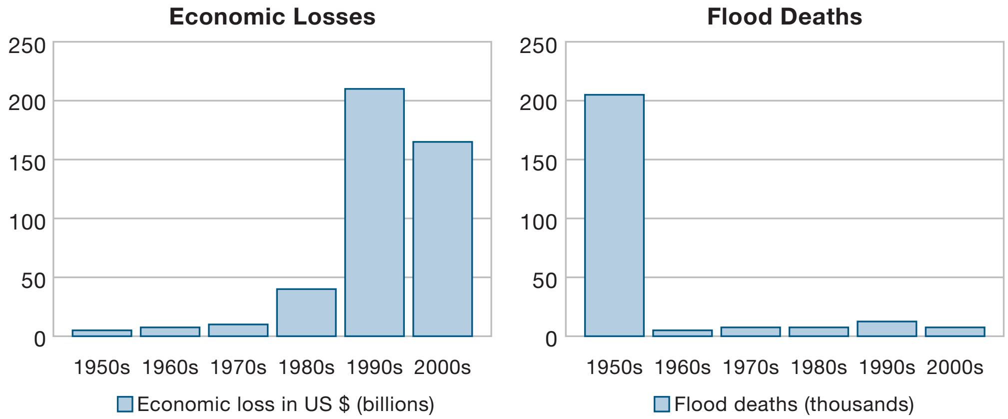

Figure 2.2: Reported economic losses and deaths. Source: based on EM-DAT/CRED

Two-thirds of direct deaths from flood events are caused by drowning and one-third by physical trauma, heart attack, electrocution, carbon monoxide poisoning or fire (Jonkman and Kelman 2005). Most deaths occur during a flash flooding event as against the slower riverine events (Du et al. 2010).

In developing countries such as Bangladesh, the majority of flood deaths have been found to be caused by diarrhea and other water-borne diseases, or from drowning and snake bites. In Vietnam, electrocution is the biggest cause of death in the immediate aftermath of flooding, followed by respiratory diseases, pneumonia and exposure to cold. Diarrhea-related deaths are primarily caused by a lack of pure drinking water, improper storage and handling of drinking water, poor hygiene practices and the often total deterioration of sewage and sanitation facilities which lead to the contamination of drinking water in flood affected areas (Kunii et al 2002; Ahern et al. 2005). These deaths can occur during the period following the reported flood and, therefore, are not necessarily recorded in disaster databases.

According to the Emergency Events Database (EM-DAT), on average over the past three decades more than one hundred million people each year have been affected by floods. This is reason enough for governments to take action towards reducing these statistics. The numbers affected have grown from around four million a year in 1950, to the present level, which represents more than one percent of the global population. The amount and seriousness of the impact on the affected population will vary and can involve physical injury or other health effects.

The most commonly reported flood-related injuries are sprains and strains, lacerations, contusions and abrasions. People may injure themselves as they attempt to escape, either by objects being carried by fast-flowing water or by buildings or other structures collapsing (Du et al. 2010). Flood-related injuries can also happen in the pre-onset phase, as individuals attempt to remove themselves, their family or valued possessions from the approaching waters (Ahern et al. 2005). Post-onset injuries are likely to occur when residents return to their homes and businesses to start the recovery and reconstruction process (WHO 2002, Few et al. 2004; Ahern and Kovats 2006). As these injuries are not monitored adequately, it is difficult to quantify the true burden of ill health due to flood events (Few et al. 2004).

The mental trauma of flooding, caused by witnessing deaths, injuries and destruction of the home, can result in severe psychological effects in some individuals. Grief and material losses, as well as physical health problems, can lead to depression or anxiety. Three types of mental health issue have been noted: common mental health disorders; post traumatic stress disorders (PTSD); and suicide (Ahern and Kovats 2006).

In the slums of Nairobi, coping responses to flooding include bailing out of houses to prevent damage to belongings; placing children on tables and later removing them to nearby unaffected dwellings; digging trenches around houses before and during floods; constructing temporary dykes or trenches to divert water away from the house; securing structures with waterproof recycled materials; relocating to the highest parts of the dwelling; or using sandbags to prevent the ingress of water.

The most vulnerable members of the community can also be those worse affected: the poor, the elderly and the youngest members of the community will often require special help and assistance. Research has found that children and the elderly are more likely to die, particularly from drowning, than are adults (Bartlett 2008).

2.3.2. Buildings and contents

Buildings and their contents can be directly and indirectly affected by flooding in a range of ways. In cities and towns, flooding in underground spaces, including subways, basement floors and utility facilities under the ground, is also typical. Direct impacts are the physical damage caused to buildings and their contents, whereas indirect effects include the loss of industrial or business processes.

The impact of flooding on housing and households can be devastating. Fast-flowing floodwaters are capable of washing away entire buildings and communities. Depending on their form of construction and characteristics of the flooding, many buildings may survive the flood but will be damaged quite extensively by the corrosive effect of salinity and damping, and be in need of substantial repairs and refurbishment.

Case study 2.3 describes the effect of flash flooding in Brazil.

Case Study 2.3: Flash floods and landslides in Brazil

Flooding in Brazil poses serious risks to people, infrastructure and businesses. River and flash floods combined with landslides is not something new for the country. It is important to highlight here that floods and landslides in Brazil, as elsewhere, not only directly affect people, buildings, infrastructure and the natural environment, but also have indirect effects, such as losses from business interruption as well as increased burdens on public and household budgets. Business interruption (e.g. caused by damage to business premises and buildings), increased travel time and costs and loss of income are indirect impacts that are often more difficult to quantify, and yet represent a significant proportion of the overall flood damage to communities.

In January 2011, floods in South-Eastern Brazil, including Rio de Janeiro and São Paulo, killed over 800 people. Over 100,000 people were left homeless and key infrastructure was destroyed. Increases in the frequency and severity of flood events are making flood risk prevention a top priority. In response to this, Brazil's major infrastructure program 'Programa de Aceleração do Crescimento' (PAC) plans investments in flood risk prevention, and President Dilma Rousseff requested World Bank support to modernize Brazil's disaster risk management systems.

Implementation of the projects is to be carried out jointly by the states and the municipalities, while the federal government provides funding. An example of flood risk prevention investment is an urban drainage project in the Baixada Fluminense region, which aims to control flooding in urban areas and will reach in total around 500,000 households. The case demonstrates the imperative for governments to attempt to help mitigate future flooding through investment in flood risk prevention measures.

Sources: Swiss Re 2011; IUCN 2011; PAC 2: http://www.brasil.gov.br/pac

Flood events can have a variety of impacts on businesses, ranging from direct physical impacts to indirect effects (to supply chains, for example). Damage to premises, equipment and fittings; loss of stock; reduced customer visits and sales as well as disruption to business activities are among the common effects experienced by UK businesses (Ingirige and Wedawatta 2011).

The characteristics of a flood, including flood depth, duration and contaminants, will influence the extent of damage caused to a building. The speed of flooding can also determine the extent of the damage: flash flooding, for example, can completely destroy properties or cause irreparable structural damage. In a slow rise flood, on the other hand, static floodwater can damage buildings in the following ways:

- Water soaks into the fabric of the building elements causing them to deteriorate. Water can soak upwards through building materials through capillary action and in hot conditions can also cause damage through excess humidity in enclosed spaces.
- Water pressure of standing water causes building elements to fail or structures to collapse
- Water can travel underneath buildings and their foundations, thus lifting or partially lifting them causing them to float away or to crack. Water can also lift building contents and they may be damaged or cause damage within a building.
- Chemicals or contaminants in the water can react with building elements or contaminate them.
- Water can cause failure of electrical systems resulting in secondary damage.

In a fast flood or coastal flood, water which flows around buildings may damage them in the following additional ways:

- Water that is moving exerts a greater lateral pressure on building elements than static water. Changing pressure can increase the stress on building elements.
- Moving water will tend to cause scour or erosion, potentially undermining buildings and causing collapse.
- Debris is carried at higher velocity and can cause severe damage due to collision.
- Fires can be caused by the collision of fuel containers with buildings.

Generally speaking, the faster the velocity of the water the greater the damage, but the depth of floodwater is clearly another important factor in determining the scale of damage. It has been found that flood depths greater than 600 millimeters are more likely to result in structural damage to buildings (USACE 1988). This relationship is normally demonstrated by a depth damage curve such as the example in Figure 2.3.

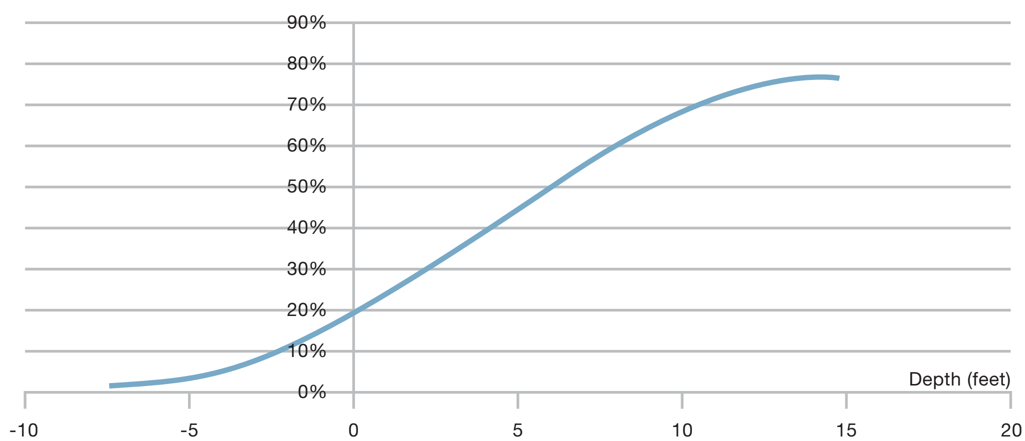

Figure 2.3: Example of a depth damage curve for one story residence with basement. Source: USACE National Economic Development Manuals

Anticipated flood depth will tend to be a deciding point for the method of flood protection. Hydrostatic head – the pressure caused by the weight of water being held above the pressure point – will place stresses on walls and any other vertical elements and will also drive floodwater through walls. If the flood depth is predicted to be greater than 900 millimeters, flood proofing is unlikely to be feasible unless specially constructed methods are used. The consensus of opinion is that the cut-off depth for wet-proof construction should be 600 millimeters (USACE 1988).

Flow velocity is presumed to be an important factor in the causation of flood damage, although hazard models rarely quantify its impact and its influence is therefore rarely taken into account. Some recent studies which have examined both water depth and flow velocity have concluded that the latter has a significant influence on structural damage, for example on roads, but only a minor influence on monetary losses and business interruption (Kreibich et al. 2009). However, it has also been recommended that if the other impact factor, water depth, is less than two meters then flow velocity alone is not a suitable consideration for estimating monetary loss in flood damage modeling and assessment.

The materials used for buildings, their drying characteristics and the condition of the building can also influence the extent of damage caused. Masonry construction, for example, is able to withstand the impact of flood waters up to a point but, being a porous material, it will absorb a large volume of water and take considerable time to dry out. Timber construction can be relatively waterproof but is often less robust. Adobe and soil based construction are more vulnerable to scour and erosion.

Building quality also has an impact on a structure's ability to withstand flooding. Flash floods within an urban environment present particularly high risks with respect to damage to buildings. As previously noted, many of the larger cities in the world which are at risk of flooding are characterized by high levels of density and congestion. For example, the city of Mumbai is extremely overcrowded which constantly threatens the city management system, leading to overburdens in sewage and wastewater, the dumping of household and commercial garbage disposals in open landfills and direct discharges to water bodies. Safety standards are also overlooked to fulfil the demand for space and development of property. As a result of the already existing difficulties in management, a flood in such cities causes havoc. Flood waters carry with them the debris of waste but also the treasured belongings of a dense and overcrowded city. The materials from buildings damaged by floodwater are also swept along. In an overcrowded space this may lead to an avalanche of further damage.

Existing buildings located in flood zones, therefore, represent a particular risk; in the light of climate change predictions, the adaptation of such buildings to future flood risk poses a considerable challenge for many countries. Regulations should also be designed to restrict or prevent new development, although it is possible that new buildings can be designed to withstand the affects of flooding by appropriate use of materials and flood resilient measures (Satterthwaite et al. 2007).

Damage caused to public buildings such as hospitals, clinics, educational buildings, and significant cultural sites such as churches can lead to further indirect impacts: for example, the disruption to education, which over a long term period can lead to children suffering academically; similarly, there is likely to be a reduction in the capacity for providing both immediate and longer term health care and support.

Release of contaminants poses serious public health risks for survivors of floods. Flood waters can mix with raw sewage and thus dramatically increase the incidence of water-borne diseases. Although the release of toxic chemicals is diluted by flood water (causing toxicity levels to decline) the uncontrolled release of various chemicals – some of which may interact with each other – poses a considerable risk to public health. Infrastructure

The UK-based Centre for the Protection of National Infrastructure (CPNI) defines national infrastructure as "those facilities, systems, sites and networks necessary for the functioning of the country and the delivery of the essential services upon which daily life … depends" (CPNI 2010). These sectors include finance, food, government, emergency services and health. Particularly at risk from flooding, are: communications; transport (roads and bridges, rail, waterborne navigation, both inland and sea, air), telecommunications; energy (power generation and distribution, petrol, gas, diesel and firewood storage and distribution); water supplies, and waste water collection networks and treatment facilities.

Case study 2.4 describes the impacts of flooding in Lomé on the city's infrastructure, and specifically the damage caused to its road systems.

Case Study 2.4: Flooding in Lomé, Togo

Lomé, the capital of Togo in West Africa, is part of a submerging coast and lagoon system within coastal dunes. The city has two wet seasons due to its location which places it between the deep rain forests of the Amazonia type as well as the Congo Basin type. The practice of illegal sand mining is becoming a serious problem as the demand for sand is rising with increasing population and the exploding construction activities currently ongoing in Lomé. The increased sand-winning activities are causing coastal erosion and subsidence, and invariably causing huge harm for the ecological balance of the coastal flora and fauna in that area of the Gulf of Guinea coast.

The coastal lowlands within Lomé are the most populous neighborhoods and suffer from excessive pressure of formal and informal settlements, poor planning in urban areas, lack of proper drainage infrastructure and maintenance, and low levels of education and social awareness among people. The Lomé city master plan that is currently in use was crafted in 1983. While its provisions and management systems configuration may have been appropriate for the time it was drafted and the population was not as high as it is today, the plan needs immediate updating. The city in 1983 had about 120 km^2 of area but today, the estimated area of Lomé is 160 km^2. The problems are made worse by a continuous influx of people to the city in search of employment and a better standard of living. In Lomé and its surroundings, called "Great Lomé", over 250,000 people live in informal settlements most of which have been built in spaces previously assigned as waterways or natural water collection points. Most of the lands occupied by the very poor people happen to also be located in mostly low-lying parts of the city thus rendering the very poor vulnerable to floods. Flooding is a constant concern and poses a severe problem because floodwater sometimes takes several months to recede; pumping techniques are not appropriate because of the saturated water table in the low-lying coastal plain.

As a result of the country's decade-long creeping political crisis leading to social and political instability there persisted a complete (a) lack of maintenance and new investments which had considerably hampered the delivery of basic municipal services, and (b) a dramatic increase in urbanization, largely compounded by crisis-led population displacement contributing to increased pressure on existing infrastructure and services in most urban centers, especially, Lomé. Over 54% of Togo's population lives in Lomé city alone (Amankwah-Ayeh and Caputo 2011).

Lomé suffered from a flood event in June 2010 in which about 200,000 people were directly affected. The estimated costs and losses were: social sector $15.5 million and infrastructure $19 million. The impacts of flooding in Lomé and Togo in general have more far reaching implications and cascading impacts. Lomé is a major communications center and port, not only for Togo but also for neighboring landlocked countries such as Burkina Faso: the main roads, therefore, carry a great deal of traffic. In 2008, due to flooding disrupting the main roads and destroying rail infrastructure, heavy traffic was diverted on to minor routes. These minor roads became unusable, turning into rivers of mud. The damage to the road system is illustrated in Photos 2.2 and 2.3.

 

Photos 2.2 and 2.3: Roads destroyed in Togo, 2008. Source: Ayeva 2011

Due to lack of funds, only a few interspersed stretches of the major trunk road linking the port of Lomé to the landlocked capitals Ouagadougou, Niamey and Bamako have been reconstructed since the 2008 floods. This was worsened by the 2010 major floods. One of the consequences of the persistent flooding in the country has been a huge exodus of people, mostly out of rural areas in the north of the country to urban centers in the south, in search of stability and economic opportunities. As a result, urban poverty and overcrowding has dramatically increased in Lomé.

Recent government initiatives have resulted in many planned preventative measures of which a minority is in place with many more in process. Achievements to date have included refurbishment of pumping stations, dredging and cleaning activities, and roadside drain construction.

The study reveals how the actions in response to flooding can lead to other indirect impacts – in this case the damage caused to minor roads by traffic diverted from main roads due to flood disruption. Again the complex relationships of direct and indirect impacts and socio-technical challenges of flooding come to the fore.

Sources: Amankwah-Ayaeh and Caputo, 2011; Ayeva 2011.

Critical infrastructure is also defined by the CPNI as those elements of national infrastructure, of which "The loss or compromise ... would have a major impact on the availability or integrity of essential services leading to severe economic or social consequences or to loss of life." Flood damage to infrastructure represents a considerable concern as it affects the ability of communities to respond during a flood and to recover after an event. Damage to critical infrastructure can represent a danger to life: damage to the road network, for instance, can prevent temporary flood defenses from being erected, as well as leading to major disruptions in the lives of people and businesses. Flooding of airports and railways can similarly create chaos for major national and international transportation hubs.

Impacts on power generation can lead to temporary and permanent power losses leading to loss of electricity, heating and lighting in some locations. Table 2.1 shows the damage to the electricity sector in Yemen by flooding in 2008.

	Hadramout-Wadi		Hadramout-Sahel		Mahara		Total Damage
Damage items	urban	rural	urban	rural	urban	rural	
a) Power plants							
Diesel power generators	0	50	200	90	220	40	600
others	10		10		4		24
b) transmission and distribution systems							
Transmission lines	880	300	220	40	140	20	1600
Distribution lines	300	150	200	20	120	20	810
transformers	120	30	70	100	40	40	400
c) transmission and distribution grids	150	50	100	20	20	10	350
others	40	10	150	20	10	2	232
total	1500	590	950	290	554	132	4016

Table 2.1: Damages to electricity services in flood-affected areas of Yemen (million YR). Source: GOY 2009

Water supplies can become disrupted and contaminated leading to health concerns. Waste water collection and treatment facilities can become overwhelmed leading to pollution and contamination of drinking water supplies. Damage to urban water systems can be much more severe than in the rural areas as shown in Table 2.2 from the earlier 2008 floods in Yemen. Urban damages again exceed rural ones.

Table 2.2: Damages and Losses in the water supply and sanitation sector

Sector	Damage	Loss	Total	Total
	Riyal Millions			US$m
Rural	1,059	66	1125	5.63
Urban water	3559	612	4171	20.86
Urban wastewater	1414	43	1457	7.29
Total	6032	721	6753	33.78

Source GOY 2009

Drainage systems can also become overwhelmed as a consequence of intense rainfall; they may also have inadequate capacity to cope with the rate of rain water runoff, leading to surface water flooding.

Box 2.1

Specific guidance on the social, economic and environmental impacts of disruption to essential services is limited. The UK's Water Services Regulation Authority, known as Ofwat, provides a framework listing the following as potential consequences of flooding-related disruption of water infrastructure:

- Loss of state revenues due to non-functioning of the private sector
- Costs associated with state support for provision of emergency supplies if interruption is substantial
- Inconvenience of interruptions due to service loss
- Health risk due to contamination of water supply and the environment
- Extra clean-up costs due to wastewater mixing with flood water and entering property
- Environmental pollution due to wastewater mixing with flood water.

Source: Ofwat 2009

The interconnected nature of modern infrastructure systems often means that failure of one system caused by floodwater can have a cascading impact on other systems which may or may not have been damaged by the flood. Loss of power, for example, may have impacts on many other systems such as water supply and communications. In particular the high dependence of most modern systems on information and communications technologies makes them extremely vulnerable to loss of connectivity.

2.3.3. Animals and crops

Within urban and peri-urban environments the impact of floods are likely to be on domestic pets and individual animals kept for personal food supply, such as poultry. Such animals can be regarded as part of the family and their rescue, or concern for their whereabouts, can delay or prevent evacuation. Floods also cause deaths and injuries to livestock and fish stocks and damages crops, although for urban populations this may represent an indirect impact, as they are less likely to be involved in agriculture than the rural population. Loss of agricultural production will, however, affect the food supply chain on which the population of urban areas are highly dependent (Weir 2009). Large-scale disasters like flooding can reduce food availability in cities, but such urban food insecurity is, for the most part, considered to be a food access problem, rather than a food availability problem. Food shortages lead to rising prices, so that the poor cannot afford to buy it as incomes decrease due to lack of work; this results in economic and financial hardship (IFRC 2010).

2.3.4. Cascading impacts

Flood events can be a catalyst for other disasters both natural and human-made, or can be part of a chain of cascading events mentioned above. A dramatic recent example of this phenomenon is the damage to the Fukushima nuclear power generator in Japan after the 2011 tsunami: a massive-scale disaster arose at the end of a chain initiated by an earthquake, as described in Case study 2.5 below.

A common secondary effect of flooding is large mudflows and landslides, as was observed in Korea in 2011. Catastrophic failure of interconnected infrastructure can also cause a man-made disaster if, for example, dam controls fail due to loss of power or flood damage. Chemical or sewage related pollution of water supply can result from damage to factories or treatment plants. In considering the impact of floods, and the benefits of prevention, the potential for cascading impacts should not be overlooked.

Case Study 2.5: 2011 Tsunami in Japan

On March 11 2011, a magnitude 9.0 earthquake, with its epicenter approximately 70 kilometers off the coast of Japan, triggered tsunami waves of up to 30 meters in height which struck Japan's coastline. More than 28,000 people died and some 490,000 people were affected. The earthquake and tsunami caused enormous damage to Japan's infrastructure including roads, railways and nuclear power plants. Preliminary estimates of the cost of the earthquake and tsunami are around US$309 billion, making it the world's most expensive natural disaster on record.

The case of Japan verifies that disasters can sometimes overwhelm even the best prepared countries and cities. Although concrete seawalls, breakwaters and other structures had been constructed along more than 40 percent of Japan's coastline, the tsunami overtopped these walls.

The result was even more devastating for the Fukushima nuclear power plant: the impact of the tsunami disabled the diesel generators that were vital to maintain power for the reactors' cooling system. The consequent malfunctions caused overheating which led to nuclear meltdown in reactors, and became Japan's worst nuclear accident.

The unprecedented crisis in the Fukushima nuclear plant highlights the risk of dependence on seawalls in particular, and other structural measures in general. Yoshiaki Kawata, a disaster management expert in Kansai University in Osaka and director of the Disaster Reduction and Human Renovation Institution in Kobe, commented in The New York Times:

"… this [disaster] is going to force us to rethink our strategy ... This kind of hardware just isn't effective."

Sources: Onishi 2011; EM-DAT (no date); UNEP 2011.

2.3.5. Post-disaster damage assessment

In the aftermath of major disasters such as floods, governments with the help of organizations such as the World Bank and the United Nations, undertake damage, loss and needs assessment, widely known as Post Disaster Needs Assessment (PDNA), in order to better plan recovery actions. Many use the Damage and Loss Assessment (DaLa) methodology, which was developed by the UN Economic Commission for Latin America and the Caribbean (UN-ECLAC) in the early 1970s. In the 2010 Pakistan floods, which have been described as the worst in the last 80 years, the assessed damage and loss estimated by the PDNA was PKR 855 billion or US $10.1 billion, which is equivalent to 5.8 percent of GDP (GFDRR, 2010).

Flood loss assessment can be carried out at various points within the event cycle: during the flood itself (thus informing the emergency response and relief coordination); in the immediate aftermath of a flood event (around one to three weeks after the flood peak); or three to six months after the event (to provide a more in-depth assessment of the full economic impact). Often the best time to conduct an in-depth assessment of flood losses is after six months, as most losses, including indirect and intangible losses, can then be assessed with sufficient reliability.

There needs to be a standard approach to loss assessments, primarily to ensure that works undertaken to provide mitigation or warning systems produce a sound return on the investment; to have a common measuring tool for assessing alternative mitigation plans; and to assist with post-disaster recovery planning and management.

Loss assessments should be transparent, so assessment procedures can be easily followed; consistent and standardized, to allow meaningful comparisons; replicable, to enable the assessments to be checked; and based on economic principles, so that assessed losses accurately represent the real losses to the economy.

2.3.6. How to conduct a flood damage assessment

It is important to perform damage assessment after any major disaster including flooding to enable a full and accurate assessment of the type and extent of damage. This damage may be a consequence of the economic, social and environmental impacts of flooding. Damage assessments might be undertaken most effectively sometime after the flooding, for example to help inform the development of flood risk management strategy at governmental level. At this time, it is more likely that the full impact of the flooding, including the indirect and intangible losses, will be known. The indirect impacts include those caused by disruption of physical, social and economic linkages of the economy and are more difficult to quantify in the immediate aftermath of the event. Typical examples are the loss of economic production due to destroyed facilities; lack of energy and telecommunication supplies; and the interruption of supply with intermediary goods. Results of damage assessments can also be used to evaluate cost-benefit appraisals when considering different flood mitigation measures and investments in specific flood defence schemes. At a more local scale, damage assessments can help inform the emergency response and relief coordination efforts in deciding how best to allocate resources and prioritize the response. It is equally important that damage assessments are undertaken in a reliable, consistent and transparent manner. Inaccuracies may lead to poor or improper investments and responses and so lead to a misuse of resources. A consistent approach provides for an evaluation of damage trends over a period of time and allows for a reliable evaluation of the benefits of flood mitigation measures.

Method

The following damage assessment methodology provides guidance towards undertaking a localised assessment of the tangible flood damage and is broadly based on that used by Jha et al (2010). The information obtained through this process will help to plan for the eventual re-occupancy of homes and businesses and provide useful information for plans for the design of new buildings including the adaptation of existing properties. Technical information on the type and nature of damage will be captured that will help inform the methods of repair and reinstatement and the resources (equipment, manpower and time) needed. The methodology involves a systematic approach which can be planned and rehearsed in advance of future flooding which will help with prompt implementation in the event of a flood.

1. Initial reconnaissance survey

2. Habitat mapping

3. **Village transect**
4. **Property-level survey**
5. **Photographic documentation**
6. **Classification of buildings**

1. Initial reconnaissance survey

An initial survey involves walking around the affected area to develop a general understanding of the extent and nature of the flood damage. This is best undertaken after the flood waters have receded and appropriate measures should be taken to ensure this is conducted safely. Personal protection equipment such as gloves, strong boots or wellingtons and a safety helmet would be suitable precautions. The information gathered at this stage will help develop a broader understanding of damage and help plan for subsequent more detailed surveys of individual properties. This will also enable plans for prioritizing next steps in the recovery process to be developed and provide information for the emergency services and others involved in the reinstatement process. The initial survey may be carried out by a team or individually by trained community workers, engineers and local officials.

2. Habitat mapping

Habitat mapping is a process of creating an aerial overview of the flood damage based on local information towards developing a visual representation of the location of damaged buildings and public spaces. Damaged property and infrastructure are identified geographically and categorized based on their damage (i.e. extent, type, severity). The map helps to provide a local understanding of the extent of damage to property and their proximities to other buildings, public areas and roads etc. Mapping can be undertaken using basic manual hand-drawn recordings or using high resolution GIS data. Information from the habitat map should be transformed into a list that is cross-referenced with public records / databases. The mapping is best undertaken by trained assessors including local officials and community members.

3. Village transect

A transect is a line following a route along which a survey is conducted or observations made and is used to analyze changes in physical characteristics from one place to another. A village transect will follow one or more streets and will show changes in the damage to buildings and infrastructure. This will help to identify emerging patterns in the type of damage to buildings and relate this damage to settlement patterns, the local geography, environmental features and other land uses. Drawings and sketches can be used to capture the extent and nature of flood damage as it relates to these features. This information is used to make decisions about environmental management, as well as relocation, resettlement and the planning and organization of the recovery process. The product of this process is flood event specific information in the context of local environmental characteristics and land uses.

4. Property level survey

Individual property surveys must be undertaken to provide detailed information for record / administrative purposes (tenure of property, owner characteristics and damage category) and for technical purposes (type of construction and materials, details of damage, reinstatement steps). This information is best recorded on a standardized survey form developed for this purpose. Checklists and prompts can be designed into the survey form to ensure consistency and completeness of the information collected. In carrying out the survey, attention should be paid to the depth of flooding as this will influence the extent of the damage and the likelihood for repair. Deep flooding can often cause structural damage to buildings which might require specialist works and in some cases the entire demolition of the building. Masonry built structures are normally able to withstand the effects of floods below say 400mm in depth but will typically absorb water and require drying out before repair works commence. Electrical services should be disconnected and checked by an approved electrician before they are used. Floodwater will usually leave a deposit of debris and sediment and this will need to be removed before repair works can proceed. These surveys are best undertaken by experienced surveyors or engineers with knowledge of buildings and materials.

5. Photographic documentation

A photographic record of each individual property serves a variety of useful purposes and can be undertaken as part of the property level survey. Insurers will find these photographs particularly useful in providing a clear record of damage to buildings and contents. This record can be used to validate other sources and will provide a basis for monitoring the reconstruction process. Local trained photographers with an understanding of the documentation process are needed to carry out the process.

6. Classification of buildings

Where no existing numbering system is in place, it is useful to create a temporary numbering system to help with the recording of information and management of the recovery and repair processes. This should follow a logical and simple format and is best designed by local community officials. Alongside this, it is useful to design a simple process of categorizing the levels of damage to buildings. This will need to be designed by qualified surveyors or engineers and some training will need to be provided to ensure consistency in its application. This combined process will serve to provide a comprehensive numbering and classification of property damage.

2.4. Indirect and other effects of flooding

In addition to the direct impacts of floods outlined above, there are indirect impacts caused by the complex interactions within the natural environment and the human use of resources in cities and towns. Such indirect impacts can be hard to immediately identify and harder still to quantify and value. Indeed, some will not become fully apparent until well after the flooding subsides. These indirect impacts can be subdivided into four major groups and are outlined below.

2.4.1. Natural environment

High rainfall can cause erosion and landslides, often on a large scale in areas of steep topography. These in turn can damage infrastructure, especially roads, which are often the only way of accessing communities affected by flooding. The erosion causes high concentrations of sediment and debris which are then deposited when the flooding subsides. Removal of the sediment and debris is costly and time-consuming. In some extreme cases, buildings and whole parts of towns may well have to be abandoned. Relocation may be the only solution, which will involve revised land use zoning.

The smothering of agricultural land by sediment can also be a problem for high value vegetable production in peri-urban zones, as a lot of such sediment is low in organic matter. Yields may never return to their previous level with resulting impacts on human livelihoods and nutrition.

Heavy rainfall can also cause damage to vegetation (whether natural or planted), and results in the reduction in the ability of vegetation to dissipate the energy of heavy rain. Primary forest cover with a high closed canopy is very efficient at dissipating rainfall energy whereas secondary regrowth or trees planted for economic reasons are less likely to have closed canopies and are less efficient in diffusing rainfall energy. This can result in less infiltration to the soil and higher levels of rainfall runoff which also further increases the risk of soil erosion and gullying (the latter being illustrated in Photo 2.4).

Photo 2.4: A gully caused by soil erosion. Source: Alan Bird

Coastal flooding in tropical areas as a result of tsunamis triggered by seismic action, or cyclones, causes damage or destruction to coral reefs which then reduces their ability to dissipate wave energy. When coupled with the fact that sea level rise in many such locations is now faster than the rate of coral growth, the risk of more severe flood events is increased. The damage to coral often increases the risk of coastal erosion.

The flooding of coastal areas with saline sea water as a result of cyclones and tsunamis renders farmland unfit for many crops, including high value vegetables that are often grown in peri-urban areas. It can take a long time and careful management to reduce the level of salinity. In many cases this may never happen. In some coastal areas such saline flooded land is converted to aquaculture with a whole set of complex issues over land ownership, land use planning, water quality and water management. After the 1991 cyclone in Chittagong, Bangladesh, for instance, such issues were further complicated by the spread of disease in saltwater shrimps which created pressure from aquaculture producers to change the water management system to supply them with non-saline rainfall runoff (Aftabuddin and Akte 2011).

2.4.2. Human and social impacts

The survivors of floods have a range of immediate needs, including safe drinking water, food and shelter. Such survivors are likely to be traumatized and vulnerable. It is a harsh truth that in cases where flood warnings, evacuations and safe havens have been successful this increases the demands after the flood in dealing with the larger number of displaced people than if these people had not survived. Lives saved during the emergency may result in increased hardship and deaths in the aftermath. This illustrates the need for flood warning and preparedness measures to be backed up by the stockpiling of immediate requirements – and also by a workable flood recovery plan.

2.4.2.1. Demographic changes

Demographic impacts of loss of life as a result of flooding can be significant, causing the age structure of communities to become unbalanced. A rapid epidemiological assessment in two cyclone devastated areas in the aftermath of the 1991 Bangladesh cyclone showed that mortality was greatest in children below the age of 10 and lowest (approximately four percent) for males greater than age 10. Further, for females, mortality increased with age and was greatest (approximately 40 percent) for women over the age of 60 (Bern et al. 1993).

The affected communities had very few elderly people left alive; similarly they had lost children who were too old to be carried, but not old enough to run inland to the main road which became the main refuge. More women than men were killed, partly because they were less physically able to run, but also as they had tried to save their children, putting their own lives at risk. It was also apparent that more girls and young women were killed than boys: the boys were often able to climb trees, whereas the girls did not, partly because of social taboos. Some years later, there was an increase in the birth rate, which was seen to be a response to 'replace' children who had perished. This created a very unbalanced age structure and, in particular, put a greater burden on women, which is often exacerbated by rising levels of post-flood gender-based violence and the negative impact of floods on women's assets, such as dowries, which often do not feature in post-disaster impact assessments.

In the case of Bangladesh, as elsewhere, these changes in demography varied greatly across the affected area, reflecting highly localized flood risk situations.

2.4.2.2. Health impacts

The impacts on human health as a result of flooding can be very serious indeed, and there is evidence that in some flood events more fatalities have occurred due to waterborne and water-related disease or injuries, rather than by drowning. During the 2007 monsoon floods in Bangladesh, snake bites were estimated to be the second most significant cause of death after drawing and contributed to more deaths than even diarrheal and respiratory diseases (Alirol et al. 2010)

Post-disaster human health is also closely associated with changes in the balance of the natural environment. For example, flooding caused by overflow of river banks, or by storm surges, alters the balance of the natural environment and ecology, allowing vectors of disease and bacteria to flourish. Outbreaks of cholera and a higher incidence of malaria can result from such alterations. Noji (2005) maintains that an increase in disease transmission and the risk of epidemics in the post-flood period depends on population density and displacement, and the extent to which the natural environment has been altered or disrupted. In 2009, weeks after back-to-back cyclones left nearly 1,000 people dead, the Philippines was grappling with an outbreak of Leptospirosis (a fatal flood-borne disease); this infected survivors from areas where dirty water had yet to subside. In a report to emergency relief agencies, Health Secretary Francisco Duque said that as of 26 October that year, there were 2,158 confirmed cases of this particular infection, with 167 deaths reported by the National Epidemiology Center (IRIN 2009).

The provision of adequate non-contaminated water supplies during and after a flood event is critical. There are often problems due to a lack of fuel to boil water for drinking. The range of measures that can be used to address this problem are outlined in Chapter 4. The main risks are diarrheal diseases including cholera, dysentery and typhoid along with malaria, dengue (although mosquito carriers require relatively clean water habitats), Leischmeniasis (also known as kala-azar) and the above-mentioned Leptospirosis, spread by contact with water contaminated by infected animal urine.

Another significant issue is the psychological impact on survivors, including delayed trauma. Many survivors, including children, will be severely traumatized. Great care is needed when dealing with this. A number of studies have shown a range of symptoms resulting from exposure to natural disasters such as flooding. Among these consequences, individuals may experience symptoms of post-traumatic stress disorder (PTSD), depression, and anxiety (Mason et al, 2010). Fischer (2005) and Miller (2005) suggest that alcohol consumption, substance abuse, and antisocial behavior increased among men in the aftermath of the 2004 Indian Ocean Tsunami in India and Sri Lanka.

Given the range and severity of health implications following disasters, the health profession has developed new approaches and new mechanisms referred to as 'disaster medicine' or 'disaster health management' (Andjelkovic 2001).

2.4.2.3. Human development impacts

The impact on long-term health and development of populations may be difficult to quantify but some research shows that severe floods can affect nutrition to the extent that children affected never catch up and are permanently disadvantaged (Bartlett 2008). Births in the immediate aftermath of disasters are likely to result in higher mortality and birth defects. After a major event, displacement or break up of families due to the death of one or both parents can have disastrous long-term effects on the families themselves and the wider community. Education can also suffer due to malnutrition effects, displacement or schools being closed. Although in wealthy areas a flood event is usually a temporary interruption which can be coped with, in poorer areas floods typically worsen poverty..

2.4.3. Economic and financial impacts

The direct impacts of flooding identified in Section 2.3 will have knock-on economic implications aside from the cost of replacing damaged or destroyed items. For example, a recent report stated that flooding is one of the major factors that prevents Africa's growing population of city dwellers from escaping poverty, thereby standing in the way of the UN 2020 goal of achieving 'significant improvement' in the lives of urban slum dwellers (ActionAid 2006).

Case study 2.6 describes how heavy rains caused extensive landslides and floods in many parts of Colombia, affecting millions of people and having a significant effect on the economy.

Case Study 2.6: Colombia's 2011 floods

Continuous heavy rains caused mudslides and floods in 28 of Colombia's 32 provinces (Departamentos). In total, more than three million people, which represents nearly seven percent of the country's total population, were displaced or suffered significant damages to their homes and livelihoods. It was probably the worst disaster caused by a natural event in the country's history: according to the national government, this flood disaster could reduce Colombia's 2011 GDP by over two percent.

The La Niña/El Niño weather phenomenon along with Colombia's geography were the major triggers responsible for the unprecedented disaster. The average amount of precipitation in some parts of Colombia in the middle of 2010 was five to six times above the average. In addition, rain-saturated mountain soil crumbled away, causing daily landslides as well as sedimentation, which raised water levels in rivers.

However as Manuel Rodriguez Becerra, former Colombian Minister of the Environment noted, flood risk had been considerably increased by human-induced activities. Deforestation and the destruction of both high-mountain and savanna wetlands has altered the water cycle in the country and have led to the more flood events, which have in turn created favorable conditions for landslides. Moreover, development has often been allowed in flood plains; poorly-designed drainage systems mean even modest rain showers can cause flash flooding. "These are natural catastrophes but, essentially, they are man-made," Bruno Moro, the UN Humanitarian Coordinator in Colombia, commented. Colombia's recent floods demonstrate the impact of human activity towards increasing flood risk – in this case a combination of deforestation, destruction of wetlands, improper development and poorly designed infrastructure – and the necessity of accounting for this impact in designing flood risk management measures.

Sources: Otis 2011; Morales 2011.

2.4.3.1. Impact on long-term economic growth

In assessing the economic impacts of flooding, care must be taken to adopt both local and national perspectives. Disasters have a large impact on those directly affected but a much smaller effect on the national economy. Some local impacts, such as the effect on the tourist trade, may be balanced by growth in trade elsewhere in the country. Typically, small to medium scale disasters may have no impact on the national balance sheet.

At a national level, studies have found a variety of relationships between disasters and economic growth. There is some evidence to suggest that frequent natural disasters can have a positive impact on national economies (Kim 2010). The process has been labeled 'creative destruction', based on the assumption that reconstruction activities result in increased employment and renewal of facilities. An article by Skidmore and Toya (2002) into natural disasters in 89 countries concluded that the frequency of climatic disasters is positively correlated with human capital accumulation, growth in total factor productivity and per capita gross domestic product (GDP) growth. Noy (2009) found that a nation's ability to mobilize resources for reconstruction influences the relationship between disasters and economics. Developing countries are therefore unlikely to benefit in the long term from disasters.

Other studies have contradicted these findings, but Kim (2010) found a difference between climate-related and geological disasters, in that the former had a positive effect on the long run economy. Loayza et al (2009) found that median level flood events had a significantly positive impact on economic growth, while larger scale floods had little effect.

2.4.3.2. Impact on development goals

As a result of the lack of insurance cover, most low income countries divert funds from other development goals to flood recovery operations after the fact. Governments may face liquidity problems in the face of massive natural disasters and have to rely on international aid, development funds or insurance to reinforce national tax revenue. Gurenko and Lester (2004) estimate that, on average, the direct cumulative costs of natural disasters in India account for up to 12 percent of central government revenues. This can have a significant impact on the national economy, resulting in important infrastructure spending being delayed or cancelled.

In addition, there will be a need to arrange a system of financing for replacement infrastructure provision, both private and public. It is likely that funding for this will be at the expense of existing ongoing development work. Economic priorities have to be set against a background of widespread need and the economic implications will, therefore, spread through a much wider part of the society than those directly impacted by flooding. The challenge is for governments and the private sector to work together to set the priorities for reconstruction.

Another post-flood impact, which directly or indirectly affects already suffering people, is the burden of debt for restoration of the economy. This puts extra pressure on people and reduces their financial ability to cope with the changed situation, making them in turn more vulnerable.

2.4.3.3. Impact on livelihoods

At the household level, livelihoods are likely to be severely undermined. The severity of this is a function of the impact of the flood on employment availability, specifically whether any members of the household have been killed or injured and the degree to which they contributed to the social and economic functioning of the household. Single-headed households, notably by women, are particularly vulnerable to the loss of livelihoods.

At the wider community level, skills which will suddenly be in demand (for instance, those needed for building replacement infrastructure) could well be beyond those available within the surviving population.

2.4.3.4. Business interruption

Businesses often fail in the aftermath of disasters due to direct damage, or to indirect impacts such as business interruption. Business may be closed down due to lack of access or failure of basic services, such as water supply, waste water collection and treatment, electricity, roads and telecommunications. This, in turn, is likely to have significant economic implications for areas much wider than the immediate flooded area. The replacement of such services can be complex (for example, starting up a damaged power station when you need power in order to do so), will take time and money, and will cause serious economic losses. The 2011 tsunami in Japan put a serious strain on the national economy and also had global impacts: as an example, the supply of

Japanese-made vehicle parts to automobile assembly plants around the world was severely disrupted.

Businesses which can continue to operate may take months to recover and to return to normal trading. The recovery process may be hampered by the loss of documentation in the flooding, leading to delays in tracing orders, completing insurance claims and issuing invoices. Other indirect effects may include increased expenses; lack of demand; the short term loss of market share; loss of key personnel; lack of availability of staff due to injury, travel difficulties or involvement in recovery operations; loss of production efficiency; loss of supplies; withdrawal of licenses; and loss of quality accreditation or approved standards. For many businesses these impacts can be catastrophic: one report suggests that 43 percent of companies experiencing a disaster never reopen and 29 percent of the remainder close within two years (Wenk 2004).

2.4.4. Political and institutional issues

A severe flooding occurrence is likely to place a serious strain on the institutional structures and capabilities that, in less developed countries, may already be weak. There will be a pressing need to clearly identify the roles and remits of both government and non-government organizations. The lack of or poor performance by government organizations can seriously undermine faith in government institutions; this happened after Hurricane Katrina in New Orleans in 2005. In some cases, political bias in allocation of funds is detectable, which may result in donors reducing the level of future disaster aid.

Another major factor can be maintaining the security of assets that displaced people have been forced to leave behind. The less well-off sections of society will be those least able to help themselves, but conversely they have fewer assets to lose. This may also have ethnic or gender dimensions, which can divide communities and lead to political instability.

2.5. Vulnerability and risk mapping

Given the seriousness and implications of the flood impacts detailed above, techniques are required for the estimation and assessment of risk. According to the United Nations Department of Humanitarian Affairs (UNDHA) the concept of risk assessment involves the survey of a real or potential disaster in order to estimate the actual or expected damage for making recommendations for prevention, preparedness and response (UNDHA 1992). This essentially consists of evaluation of risk in terms of expected loss of lives, people injured, property damaged and businesses disrupted. Based on the existing definitions, risk is the product of hazard and vulnerability and can be mathematically expressed for a given event in a particular area and reference time period.

Hazard assessment is explained in detail in the previous chapter. The associated factor for risk assessment, vulnerability, will be dealt in the following section. Assessments are mainly based on the depth of flood water and they are further used for risk analysis and evaluating the cost of damage. The main philosophy behind evaluation of risk is to provide a sound basis for the planning and allocation of funds and other resources. The framework of risk assessment illustrated by WMO (1999) indicates that evaluation of hazards and vulnerability assessment should proceed as parallel activities, in a consistent manner, so that results may be combined and comparable. For example, two cities may be equally vulnerable, but could have very different exposure to the hazard, depending on their elevation. The main problem in doing so is the availability of organized data, especially in developing countries – and the cost and effort needed to acquire data.

The basic steps involved in a risk assessment process are:

- Hazard estimation with reference to location, level of severity and the frequency of event occurrence
- Estimation of exposure of elements at risk
- Estimation of vulnerability
- Estimation of risk by integrating hazard, exposure and vulnerability.

As indicated earlier, in most cases risk assessments are performed based on direct damages. Indirect damages, also known as 'second order' effects, are often ignored leading to underestimation of the total cost of flood damage. It can be difficult to get appropriate data for indirect damage assessment, the main problems being measuring accurately the ripple effects on the economy and impacts on infrastructure and communication disruption. In addition, historical data do not disaggregate the total loss into direct and indirect losses; discrepancies in data can arise when gathered on a survey basis and there may be non-cooperation in disclosure of financial losses by affected people and companies. The assessment of second order risks is, however, achievable if appropriate data is available. In order to perform a comprehensive risk assessment, thus reducing the difference between actual and estimated damage assessment, integration of primary and secondary sources of damage assessment and risk evaluation is necessary.

In areas of multiple hazards the risk is sometimes cascading in nature. It might not be generated by natural sources, but accompanies an event or follows immediately afterwards. Flooding leaves a large amount of debris in its way, disrupting normal drainage and transportation systems. It may also cause fires and electrical short circuits, leading to more damage and destruction. Salt water contamination in coastal regions can also affects water supply lines, as well as contributing to the rate of deterioration of property and other assets.

In addition to raw sewage spills and debris, flood water may also contain toxic materials, leading to pollution of the local environment. There are occasions when a landslide or earthquake causes flooding: this is particularly true in multihazard areas where one disaster leads to another, resulting in a much greater incidence of damage and destruction.

Case study 2.7 discusses risk assessment issues within the context of the most significant international flood events in recent times in Pakistan.

Case Study 2.7: The 2010 Pakistan flood and the challenges of risk assessment

In July and August 2010, Pakistan was hit by extreme rainfall leading to devastating flooding that killed more than 2,000 people and affected more than 20 million. The areas most affected by the overflow of the Indus River coincided with the districts with the highest population density. This is because population in this semi-arid area has concentrated near to sources of water.

The onset of the flood event was intense monsoon rainfall on the last three days of July and the first days of August. In the northern part of the catchment, this led to a sharp peak in the river level. Continuous heavy rains then further enforced the flood wave as it moved downstream.

More deaths were reported in the upper catchment where the river gradient and flow velocities were highest. The flood event in the upper catchment area was significantly higher than previous maxima in the 66 years of records. Extrapolation from the gauging station data indicated that for the upper catchment this corresponded to a 1000-year return period, and in the mid-catchment to an 86-year return period. Downstream, the semi-arid areas were more accustomed to deal with water shortages, rather than flood disasters.

Flood monitoring and prediction along the River Indus during such events is problematic. While flood arrival times along the river are relatively easy to predict (the lead times were as much as 10 to 15 days in the southern parts of the country), the propagation of the water in the floodplains is not. There are strong interactions between the main channel of the river and its wide irrigated floodplain, which extends to as much as 20 kilometers across at peak discharges. The unpredictability is exacerbated by the uncertain state of repair of embankments: where these fail, the water immediately and unpredictably inundates the areas behind them. This case reveals how previous flood events may not be a reliable source in predicting future flooding. The complexities involved in predicting propagation of the water are considerable, and uncertainty in the state of embankment repair can lead to further unpredictability.

Source: Straatsma et al. 2010; NDMA Pakistan: http://www.ndma.gov.pk

As discussed above, the impact of floods on the urban environment is caused by the action of hazard on exposed and vulnerable receptors. Changes in impacts from flooding can, therefore, result from changes in the hazard; changes in the exposure of populations and their assets; or changes in the vulnerability of the exposed populations and assets. To understand the potential impact on a community and the appropriate response, flood risk maps are an invaluable tool: they provide the foundation upon which a well-planned risk management strategy can be built. They assist decision makers to make cost benefit assessments, to prioritize spending, to direct emergency assistance and to design and implement mitigation activities of all kinds. Risk maps are also necessary for financial planning and insurance purposes.

Flood risk maps are built upon the flood hazard maps which were discussed in Chapter 1 and on the understanding of the impact of different flood events on the exposed population and assets. In this chapter the impacts which lead to damage and loss have already been outlined. In order to quantify flood risk completely, it is necessary to estimate the expected losses from potential future flood events, based on the best understanding of impacts. Most risk assessments will start with an assessment of losses due to physical direct damage using a stage damage function and asset database.

Extension of risk analysis to incorporate indirect and intangible losses is rarer. Such damage calculations include other sources of uncertainty such as the valuation of non-market goods and affected services (like ecosystems and biodiversity) and the choice of discount rate or any other means of dealing with time preference (Hall 2008; Merz 2010).

2.5.1. Assessing vulnerability

Vulnerability is the degree to which a system (in this case, people or assets) is susceptible to or unable to cope with the adverse effects of natural disasters. It is a function of the character, magnitude and rate of hazard to which a system is exposed, its sensitivity (the degree to which a system is affected, adversely or beneficially) and its adaptive capacity (the ability of a system to adjust to changes, moderate potential damages, take advantage of opportunities or cope with the consequences). The different types of vulnerability and the factors affecting their rate of exposure are shown in Table 2.3.

Types of Vulnerability	Exposure factors
Individual or household vulnerability	Education, age, gender, race, income, past disaster experience
Social vulnerability	Poverty, race, isolation, lack of social security services
Institutional Vulnerability	Ineffective policies, unorganized and non-committed public and private institutions
Economic Vulnerability	Financial insecurity, GDP, sources of national income and funds for disaster prevention and mitigation
Physical Vulnerability	Location of settlement, material of building, maintenance, forecasting and warning system
Environmental Vulnerability	Poor environmental practices, unprecedented population growth and migration
System vulnerability	Utility service for the community, health services, resilient system
Place Vulnerability	Mitigation and social fabric

Table 2.3: Different types of vulnerability and the factors affecting their rate of exposure

To measure vulnerability at different scales, hazard researchers have used numerous strongly correlated variables, such as the physical, social, economic, and political condition of the area of occurrence. Some of the major factors which increase vulnerability to urban flooding, especially in developing countries, are: poverty; poor housing and living conditions; lack of preparedness and management of flood defenses; increasing population; development of squatter settlements in hazard prone regions; poor maintenance of drainage structures; lack of awareness among the general population; and limitations in early warning systems.

Vulnerability assessment is carried out in order to identify the most vulnerable sections of the society and thus prioritize the assistance by channeling resources. Undertaking a vulnerability assessment therefore requires consideration of: the location of the area; resources under threat (both population and physical elements); level of technology available; lead time for warning; and the perceptions of residents regarding hazard awareness (ADPC 2005). Mapping vulnerability can help the policy makers and managers to identify the areas of highest susceptibility and impact, in order to reduce vulnerability and enhance capacity building, by concentrating efforts in those locations.

Case study 2.8 describes a comprehensive vulnerability study of a city in western India.

Case Study 2.8: Surat vulnerability analysis, India

Surat is a coastal city located in the state of Gujarat along the tidally-influenced Tapti River in western India, approximately 250 kilometers north of Mumbai. In the last four decades, the city recorded one of the highest growth rates in the country and a 10-fold population rise. About 20 percent of the city's population lives in 420 slums.

Many of these slums are located along the tidal creeks and the riverside, and are therefore highly exposed to flood risk. Flooding, coastal storms and cyclones, as well as sea level rise, are among the current climatic threats Surat must cope with.

A city wide vulnerability assessment was recently carried out using a GIS-assisted vulnerability assessment technique. The UK's Department for International Development's (DFID) livelihood framework, adjusted for the urban context, was employed for the vulnerability analysis. With regards to disasters, the vulnerability analysis found that:

- A low educational capacity among lower income groups and slum dwellers is one of the main constraints to raising awareness and implementing effective resilience strategies
- Surat has one of the highest per capita incomes in India. However, about one-third of its households experience income instability, as more than 75 percent of the lower income groups and slum dwellers work in semi-skilled or unskilled jobs, and approximately half of the middle class population relies on informal trade. As a result, these population groups are highly vulnerable to changes in the city's economy, disasters or other external shocks
- The data also suggest that lower income groups, slum dwellers as well as migrants, have weak social networks while NGOs and micro-finance coverage is limited, meaning that other ways to increase social capital have to be explored
- Among the poorer socio-economic groups, insurance coverage is low. As a result, they suffer considerably during disasters and need more time to recover
- Lower income groups and slum dwellers as well as upper socio-economic groups both live in locations exposed to floods, resulting in increased physical vulnerability independent of socio-economic factors.

The Surat vulnerability study reveals the implication of low educational capacity, income, social networks, insurance and location for vulnerability. All of these factors have to be considered in prioritizing investment and other social interventions in the cause of flood risk management.

Sources: ACCCRN 2009; SMC n.d.; Bhat 2011.

2.5.2. Vulnerability maps

Vulnerability maps are based on two major factors: the location of the elements at risks (buildings, roads, bridges, settlements critical infrastructure and utilities); and the vulnerability of those elements to different aspects of flooding (flood height, duration, sediment concentration, velocity of water, impulse and level of pollution). Development of vulnerability curves, or stage-damage curves, can be plotted based on different classes of land use, to specify their values in relation to the magnitude of flooding (Smith 1994).

Vulnerability can be expressed as the degree of loss resulting from occurrence of a natural phenomenon on a scale of 0 to 1, where 0 indicates no vulnerability and 1 is the highest level of vulnerability. This helps in prioritization of mitigation activities. The stage damage curves can be developed in two different ways: either from the actual damage survey from an event, or based upon a hypothetical scenario of an event. The data for the stage damage function are normally obtained from existing inventories, such as cadastral maps, land use maps and information from land valuation or registration offices. Information on the materials used to construct buildings is required, as well as an indication of the condition (whether in a good state of repair, for example). Obtaining such detailed data on an individual level is quite difficult in many cases, especially in countries with weak asset data systems. The survey is conducted based on the value of different classes and a potential valuation curve or stage damage curve is prepared; based on these, a flood vulnerability map can be prepared using GIS software to assign values per pixel for the entire affected area. The map will then indicate the level of vulnerability that each land use type is exposed to, based on their indicative values from the depth-damage curves.

Flood management in an area can be made highly effective by means of vulnerability zoning, in which areas classified from higher to lower levels of vulnerability. This further helps in the proposition of flood defense mechanisms, effective flood control measures, evacuation planning and flood warning. Figure 2.4 illustrates how factors like the velocity of water and water depth (the main impact factors) help in developing flood hazard maps, and in turn, in identification of the areas of highest vulnerability based on a land use map. This gives an indication of which areas need to be evacuated most rapidly, as well as showing areas suitable for temporary refuge. Table 2.4 summarizes the methods that can be used for vulnerability at different scales of interest, from national down to local.

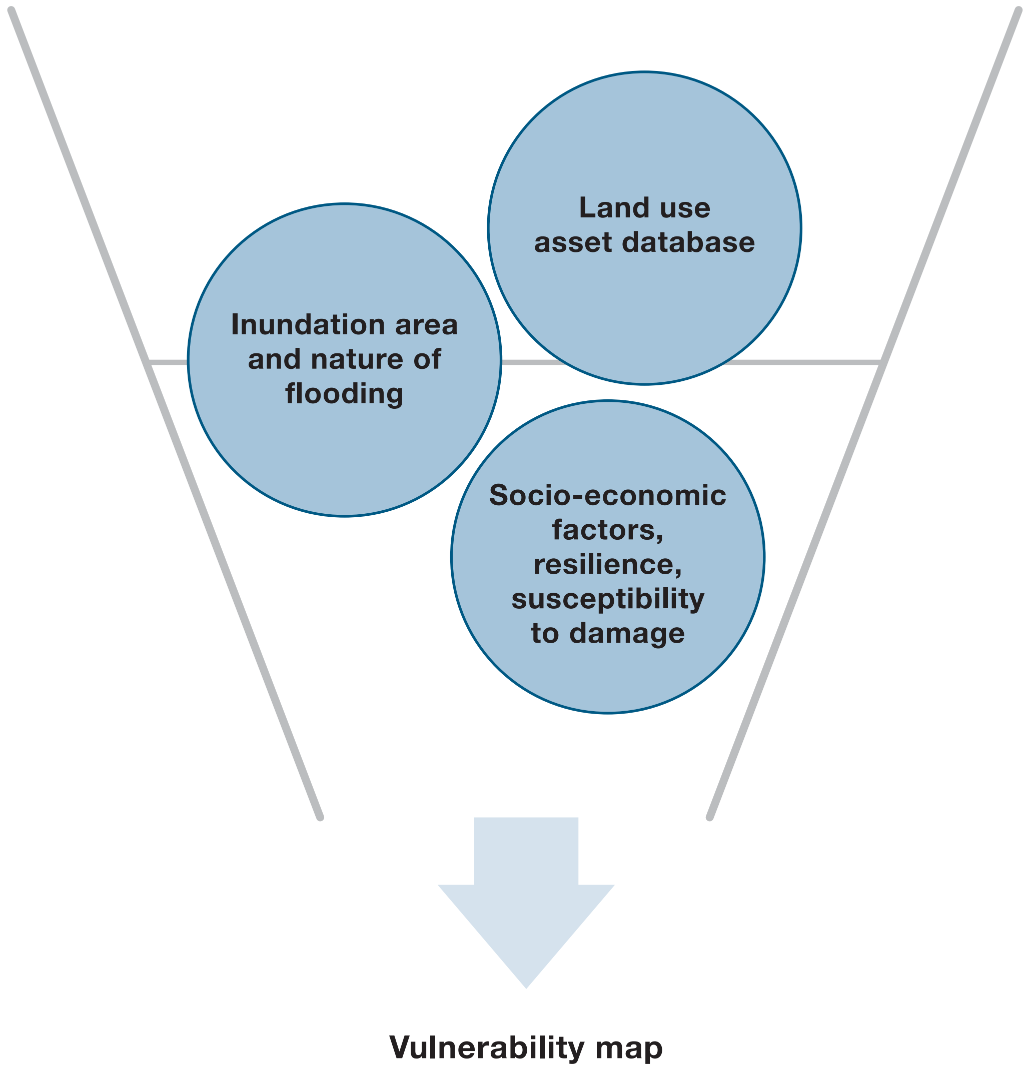

Figure 2.4: Flood Vulnerability assessment in urban areas

Table 2.4 Vulnerability assessment methods at different scales:

Serial number	Methods	Remarks
A	National Level	
1	Disaster Risk index by BCPR-UNDP	Based on historical vulnerability, for example mortality and level of damage; simple and straightforward
2.	Hot spot model by World Bank	Calculated to get vulnerability coefficients; based on disaster related mortality and losses
3	Composite vulnerability index for small island states	This method is event specific.
4	Small island states: natural disaster vulnerability indicator	Uses five specific indicators of vulnerability; representation via scale of 1-4, (1 being of highest vulnerability and 4 the lowest)
B	Megacity level	
1	Mega city level vulnerability assessment by Munich Re	It is important for understanding the level of vulnerability of the existing infrastructures and population; does not take into account historical disasters
C	Local Scale	
1	Vulnerability assessment at local level	Data acquired from local offices at municipal level, questionnaires and national archives, where available; several factors are used to assess vulnerability
2	Household sector approach	Effective for high magnitude event; surveys individual households to gather data about their level of vulnerability
3	Vulnerability at community level	This approach provides a comparative vulnerability analysis between communities in an area; data is primarily collected through questionnaire surveying and interviews
4	Normalizing vulnerability and risk community comparison	Vulnerability is accessed at town and city level by integrating data from aggregation of parameters at this level
5	Holistic approach	Method combines the approach as represented by exposure rate, social fragility and lack of resilience measures; easy to apply in cities but needs specific survey to gather information

Source: Adapted from Villagran de Leon 2006

2.5.3. Flood risk maps

Areas at risk of flooding can be dynamic in nature. With a changing level of development, the nature and degree of risk also changes. Flood risk increases mainly because of an increased level of exposure of the elements under threat. For example, there are occasions when infrastructure or other buildings are constructed in areas already at risk, thereby automatically falling within a risk zone. There are also instances when, at the time of construction, the assets and infrastructures are thought to be outside the risk region, but there are newer effects arising from changing land uses as urban development proceeds. These can include increased rates of runoff, lack of drainage systems, lack of storage systems, overwhelming amounts of rainfall leading to overflow, and the channelization of rivers which may reduce the amount of discharge they can accommodate. All these factors can increase the number of elements at risk of flooding in an area. Continuous updating and monitoring of risk maps is, therefore, most important for proper flood risk management: decision-makers need up-to-date information in order to allocate resources appropriately.

Flood risk maps represent a spatial integration of the hazard, exposure and the level of vulnerability. They effectively combine vulnerability maps with flood hazard maps to give an overall view of risk, as illustrated in Figure 2.4.

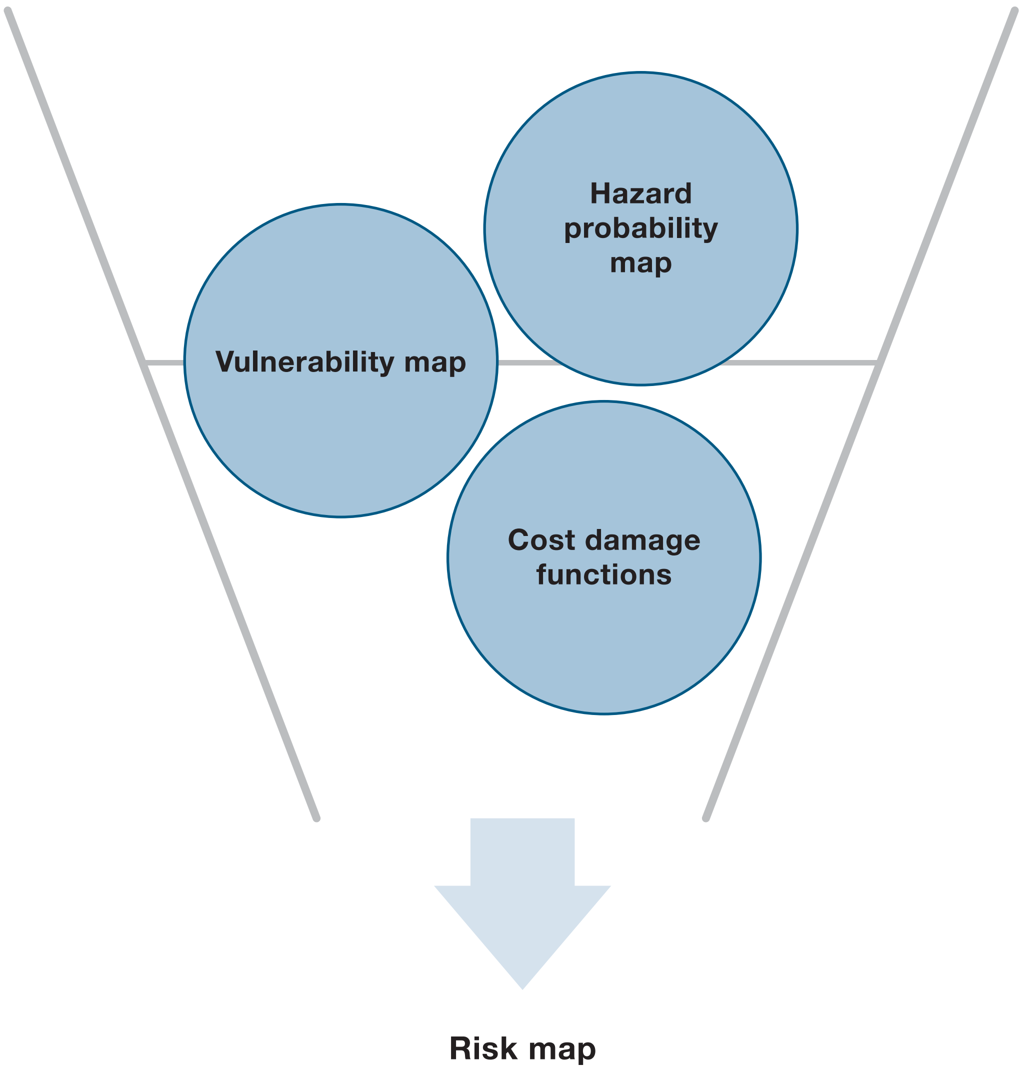

Figure 2.4 Generation of risk map.

The hazard maps provide information on the probability of flooding for different return periods, as well as the depth and extent of the flood water in the affected area. It has been argued that, even without an increase in flood hazard over time, the impact of flooding has risen (and will continue to rise) because of the increased exposure of primary and secondary receptors (Changnon 2003). There are other factors that are potentially quite significant, but may be difficult to quantify: changing risk due to societal factors, (such as development in and near floodplains), land surface alteration, the dynamic nature of social systems in general and societal vulnerability to flooding in particular (Moors 2005).

Numerous sources of uncertainty are present in the formal calculation of risk, as discussed in Section 1.3.2; flood damage prediction depends on approximations in hydrological and hydraulic models, including the neglected contributions to flooding such as debris, structure failures, and local storm water drainage.

There may be differences of opinion when it comes to the decision-making process in assessing the areas of highest risks. It is, therefore, a prerequisite to appraise these areas to an appropriate level, in order to identify the best strategies for risk reduction. This requires special attention to the magnitude of flooding (from the flood hazard maps) and the identification of the vulnerable elements (from the vulnerability assessment criteria). The spatial distribution of the vulnerable elements shown by the flood risk map will then identify clearly the areas of concern and their level of risk. The decision-making process also depends upon other factors, such as perception of risk in relation to cost-benefit analysis, measures taken for risk reduction strategies or alternatives available for risk mitigation. The risk map is, however, the core component of the flood risk management strategy.

2.5.4. Considerations for flood risk mapping

Risk evaluation is the basis for the design of methods to prevent, mitigate and reduce damages from natural disasters. Although there are several available methods for assessment of risk, it has been observed that in many cases societies prefer to set arbitrary standards as the basis for risk mitigation.

Without a clear and detailed evaluation of risk, those with responsibility for planning will have inadequate information for allocation of resources for mitigation purposes. This makes it more important to have a standard method for preparation of flood maps as a utility tool for the decision makers. Table 2.5 below presents key issues for flood risk mapping.

Actions	Considerations/ operations	Outputs / benefits
Data Collection and Integration	Actual event data, historical data, socio-economic and physical data Sources: local municipalities, regional or national data archives, international organizations like WMO, EM-DAT, existing vulnerability curves for different countries Field Surveying Hypothetical scenario generation for modeling vulnerability	Output in the form of database Important for integration of data from different sources and for future vulnerability analysis of the elements at risk
Generation of stage damage functions or vulnerability curves	Depth of flood water for different return periods Value of the elements at risk depending on their location, condition, material of construction, number of floors, and existence of cellars Extracting data by graphically representing the percentage of damage of the elements at risk to depth of flood water due to lack of resilience and adaptive capacity	Vulnerability curves are important for identifying the level of damage that has been (or can be caused by) different water depths
Conversion of depth-damage-curves to vulnerability maps	Importing data to GIS software (Arc GIS (ESRI), ILWIS (Integrated Land And Water Information System; open source), GRASS (Geographic Resource Analysis Support System; open source) Map classifications based on high, medium and low vulnerability	Conversion of results to an accessible, visual format as maps Essential for illustration of zones of high, medium and low vulnerability for action prioritization
Using vulnerability maps for risk assessment	Integration of hazard maps and vulnerability maps to produce risk maps	Output is in the form of maps showing high, medium and low risk areas Utility tool for decision making to local, regional, national and global authorities

Table 2.5 considerations for flood risk mapping

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Part of the six kilometer long levee which locals had built to protect the small town of Warracknabiel from a 'once in 200 years' flood in Victoria, Australia (2011). Source: Gideon Mendel

Chapter 3

Integrated Flood Risk Management: Structural Measures

Chapter 3. Integrated Flood Risk Management: Structural Measures

3.1. Introduction

Chapter Summary

This chapter is focused on structural measures that are used to control the flow of water both outside and within urban settlements, within the context of an integrated approach to urban flood risk management. The measures described include what are traditionally viewed as structural hard-engineered solutions, such as drainage channels, as well as more natural and sustainable complementary or alternative measures, such as wetlands and natural buffers. The chapter starts with a discussion of the integrated approach to flood risk management. The focus then turns to structural measures themselves.

Questions answered include:

What is an integrated approach? What structural measures may policy-makers consider for mitigating flood risk in urban environments? In which cases are structural measures effective?

The key messages from this chapter are:

- An integrated strategy usually requires the use of both structural and non-structural measures.
- Structural measures range from heavily-engineered interventions, such as floodways and reservoirs, to more natural approaches like wetlands and greening measures. They cover water management at the catchment and urban level.
- Heavily-engineered structural measures can be highly effective when used appropriately, but they share one characteristic: that they tend to transfer flood risk from one location only to increase it in another. In some circumstances this is acceptable and appropriate, while in others it may not be.

Human settlements have been protected by flood risk management measures for as long as they have existed. The success of traditional methods in limiting flood damage coupled, somewhat contradictorily, with the experience of continued flooding despite such measures, have resulted in guiding principles and lessons for flood risk management. The modern approach which has emerged is often referred to as integrated or holistic. In 21st Century urban environments, which are much more complex and often much larger than their historic counterparts, action is required at a much larger scale. Integrated flood risk management, which usually includes both hard-engineered structural and non-structural management measures, is required to reduce flood risk.

Within this perspective, risk managers for urban areas should consider the catchment as a whole, as the most effective risk reduction measure may be an upstream or offshore approach. However, as it is unrealistic to expect to keep all flooding away from towns and cities, flood risk managers face the additional issues of the increasingly complex behavior of flood waters once they reach the urban built environment. The interaction of floodwater with concentrated population centers, buildings and urban infrastructure is characteristic to urban flooding and requires a specific set of solutions.

Section 3.2 defines integrated urban flood risk management and gives an overview of flood risk management options, both structural and non-structural. The chapter goes on to examine structural measures in detail. Non-structural measures, aimed at keeping people safe from flooding by the planning and management of urban environments, are then covered in Chapter 4.

Section 3.3 describes the purpose of conveyance, which is the provision of a route to take potential floodwater away from areas at risk.

Flood storage measures aimed at reducing the peak of flood flows are discussed in Section 3.4.

Section 3.5 deals with urban drainage systems, while 3.6 focuses on infiltration in urban areas.

Section 3.7 is concerned with groundwater management, which is necessary to prevent land subsidence which can lead to greater problems in low-lying areas.

The following section, 3.8, outlines a set of measures that can be considered for reducing the amount and speed of rainwater runoff in urban areas by utilizing wetlands and creating environmental buffers.

Section 3.9 pays attention on the design of buildings that can reduce their vulnerability to flood impact and can therefore reduce the residual risk of flooding and enable occupation of floodplain areas.

Flood defense measures that aim at reducing the risk from flooding of people and the developed and natural environment are discussed in Section 3.10.

Finally, Section 3.11 considers defenses against estuary and coastal flooding, stemming from tides, storm surges and tsunamis.

3.2. An Integrated Approach to Flood Risk Management

Flood risk management requires the holistic development of a long-term strategy balancing current needs with future sustainability. An integrated strategy usually requires the use of both structural and non-structural solutions. It is important to recognize the level and characteristics of existing risk and likely future changes in risk. This has been discussed in Chapters 1 and 2. Reducing that risk then involves a set of measures which individually contribute to risk reduction. After measures have been adopted there will remain a residual risk.

This Chapter covers measures which are designed to control flood water, usually by physical construction or by environmental management. Chapter 4 covers measures which are designed to keep people safe from flooding by the planning and management of urban environments. These are often referred to as "non-structural" or "soft" measures. The two types of measures are complementary to each other and both form part of the integrated approach.

Integrated flood risk management also includes the recognition that flood risk can never be entirely eliminated and that resilience to flood risk can include enhancing the capacity of people and communities to adapt to and cope with flooding. Four capacities for reduced vulnerability and increased resilience are illustrated below in Figure 3.1.

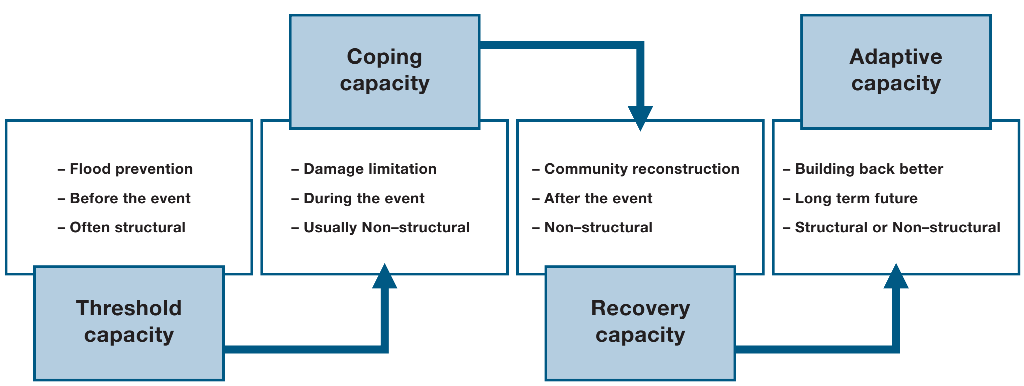

Figure 3.1: The four capacities towards increased resilience.

Flood risk reduction, for urban areas as political or economic units, must be considered at a range of scales, including the river and water catchment as a whole. This is because the source of flooding may be at some distance from the affected receptor (in this case a town or city). The best option, therefore, may be to tackle the flooding problem before it reaches the urban environment. The following figures illustrate the types of flood risk reduction measures that may need to be considered at a range of different spatial scales to create an integrated flood risk solution.

The selection of possible solutions will involve identifying technically feasible sets of measures designed to address the particular flooding scenario and should be carried out in consultation with experienced technical specialists. The development of the final strategy should be carried out through a participatory process involving all those people and institutions that have a vested interest in flood management, including people at risk or directly impacted by flooding. The established methodologies for such a planning approach are given in Chapter 6.

Figure 3.2 illustrates multiple risk management techniques in their appropriate catchment locations surrounding an urban settlement.

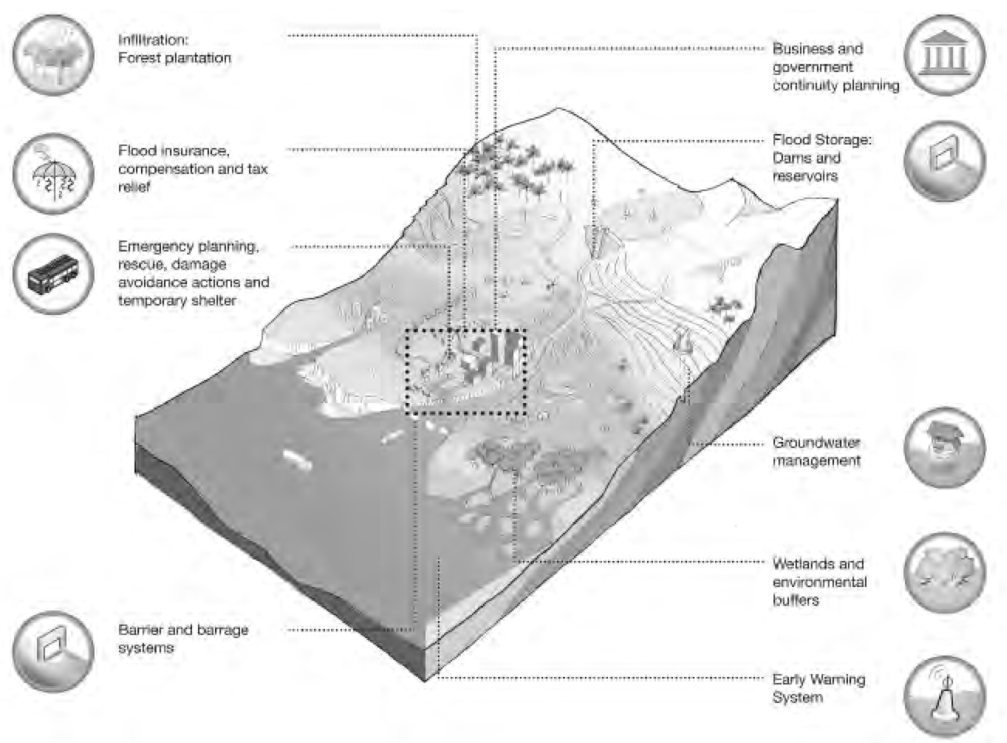

Figure 3.2: Overview of flood risk management options, catchment scale, Source: Baca Architects

Figure 3.3 illustrates measures that may need to be considered at a town or city scale, with emphasis on city defenses, land use planning and other planning level measures.

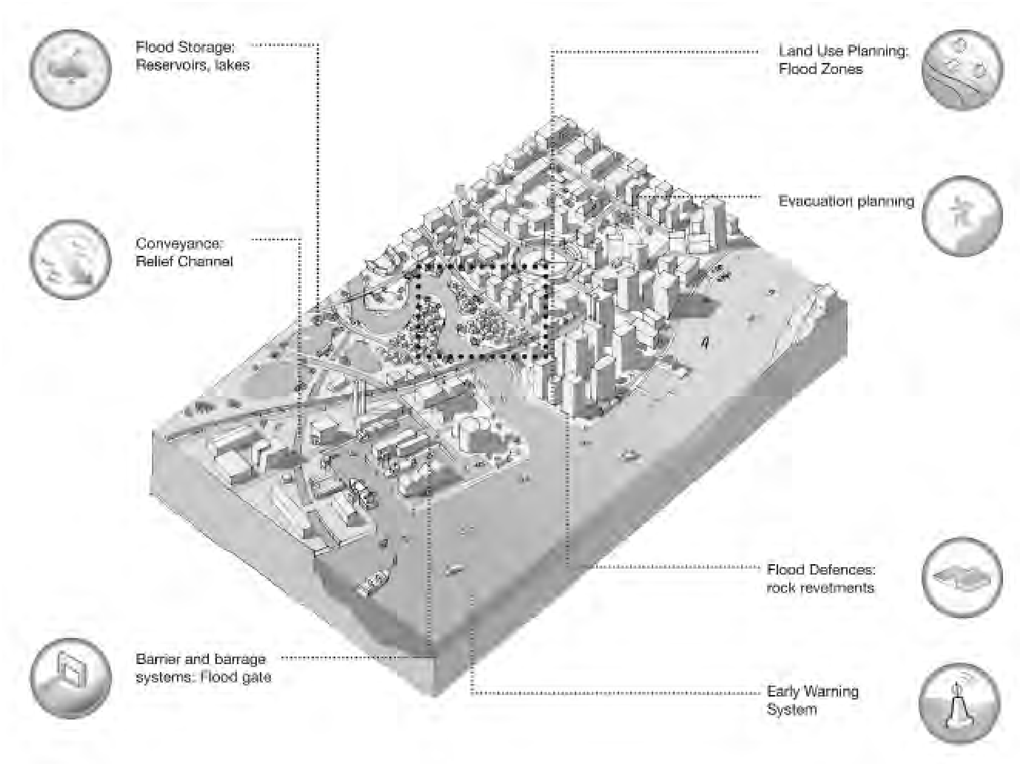

Figure 3.3: Overview of flood risk management measures, city scale, Source: Baca Architects

Figure 3.4 below illustrates measures that may need to be considered at a neighborhood or community scale, including structural and non-structural.

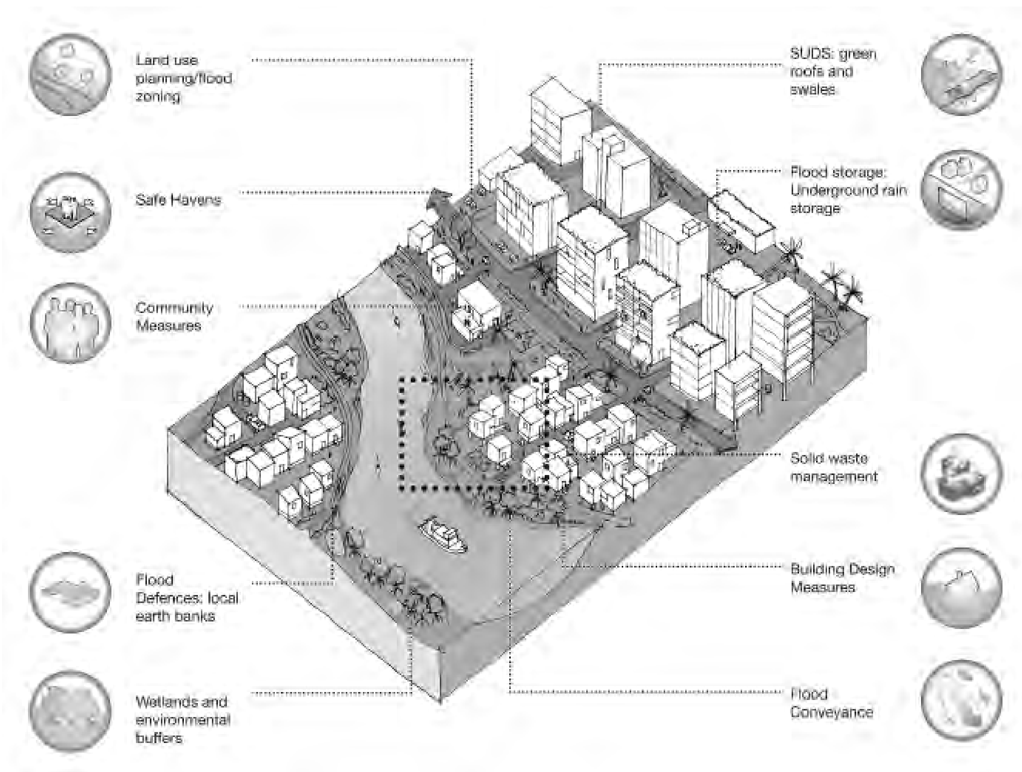

Figure 3.4: Overview of neighborhood flood risk management measures, Source: Baca Architects

Figure 3.5 illustrates building level measures and the responsibility of individuals in flood risk reduction.

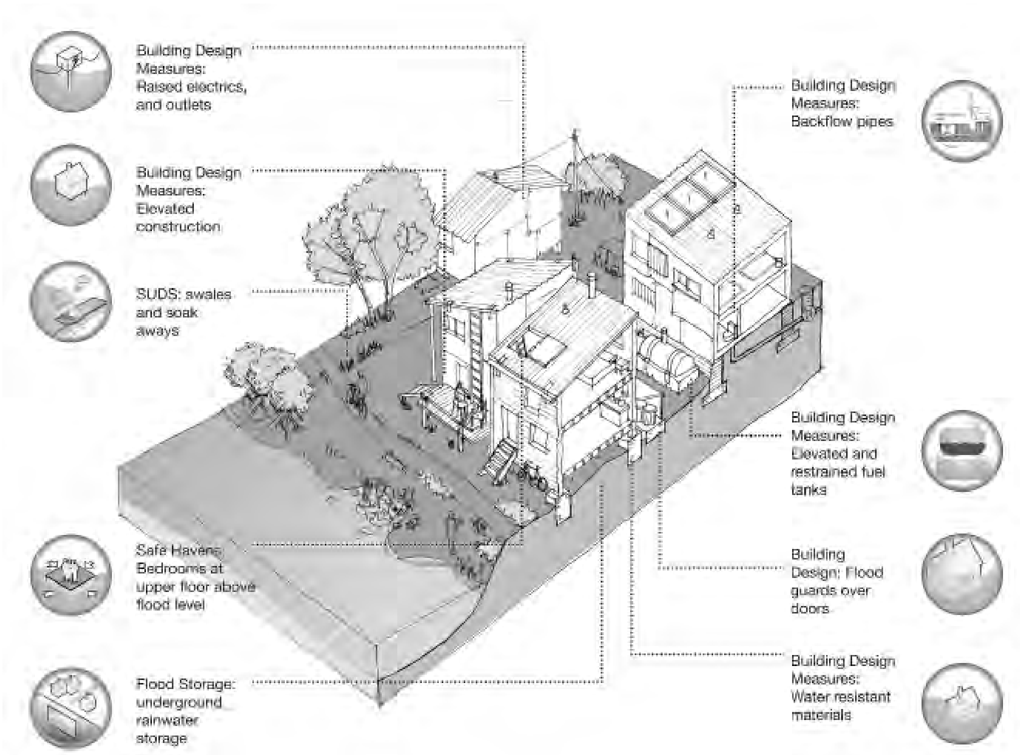

Figure 3.5: Overview of flood risk management measures, building scale, Source: Baca Architects

Both temporal and spatial issues should be taken into account when determining strategy. Structural solutions such as flood defenses and conveyance systems can form a long-term solution to flood risk, rendering floodplains habitable by protecting existing settlements. However, particularly in the developing world, they may be seen only as longer-term goals requiring large investments which will not always be available. Non-structural solutions such as flood warning systems, evacuation planning and coordinated recovery procedures are also necessary for the protection of the populations of cities and towns already at risk of flood, whether protected by defenses or not. Measures which can be implemented more quickly (such as operations and maintenance, greening of urban areas, improved drainage, building design and retrofitted protection measures) can also enable occupation of flood risk areas while minimizing the expected damage from flooding.

At the same time, one of the major tools for heightened resilience against the increasing risks caused by growth of urban population, and the expansion of urban settlements, is the redirection of such settlements away from areas at high flood risk. The use of urban land use planning can reduce both exposure to flood hazard and the run-off into urban areas. In the urbanizing developing world, the opportunity to better plan the formation of new settlements and new buildings is central to preventing the predicted increases in future flood impacts from being realized. It is realistic to recognize that floodplain development is likely to continue, due to pressure on land and other political and economic considerations. However, where new settlements are planned – rather than just occur – within areas at risk from flooding, flood-adapted design can be employed at a lower cost during the building phase than would be the case if retrofitted.

Non-structural measures need to be seen as potentially applicable to all types of urban settlements. However, given the differences in the future challenges faced by urban settlements worldwide and their development goals and resource constraints it is not possible to be prescriptive in the application of management strategies. The specific solution, or set of solutions, which is optimal in a particular location can only be arrived at after extensive evaluation, cost benefit analysis and consultation with multiple stakeholders. The measures selected will need to be negotiated with the relevant stakeholders, and will need to be adaptable to natural, social and economic conditions which can be expected to change over time.

3.3. Conveyance

In the context of flood risk management, the purpose of conveyance is to provide a route to take potential flood water away from areas at risk. Traditionally this has been seen as a way to remove the problem of flooding from the urban environment. Such systems often form part of a much broader water management approach including, for example, hydro-electric schemes in which control of excess flows forms a part.

3.3.1. Means of conveyance

Conveyance may be given effect either via natural or artificial channels. In remote areas, rivers may be in a completely natural state; in many parts of the world, rivers have been heavily modified; and in particular contexts, flood conveyance may be achieved by purpose-built artificial channels.

When water flows in any channel it must have sufficient energy to overcome the frictional resistance to flow created by the contact with the channel bed and sides. This energy is effectively provided by the slope of the channel. The capacity of a river or channel is a function of three main factors: the transverse cross-sectional area, the slope, and the frictional resistance. In a long channel with a constant area, it is possible to visualize 'uniform flow' in which the depth does not vary with distance; in this case there is equilibrium between the energy provided by the slope and the energy needed to overcome frictional resistance.

It should be noted that in addition to the general meaning of transferring flow, 'conveyance' has a specific definition in hydraulics: it is a combination of all the properties, apart from slope, that determine the capacity. Thus, if one channel construction is to be replaced by another for a particular length, assuming the overall slope cannot be changed, the conveyance of the new construction should not be less than the old, if a reduction in capacity is to be avoided.

The relationship between the physical properties of the river channel, the flow-rate and the water depth can be simulated for both steady (time-constant) and unsteady (time-varying) conditions using well-established software modeling packages. This can be linked to rainfall-runoff generation to represent flood conditions, and potentially be used to predict the development of a flood event in real time.

3.3.2. Conveyance and storage

The concepts of conveyance and storage (the latter is examined in Section 3.4) are closely linked. Any storage has the effect of attenuating (reducing the peak) of flood flows. As depths increase in a length of channel with no additional inflows from tributaries, storage within the channel itself is utilized, and so there is attenuation as the flood flow moves downstream. Attenuation also occurs when the storage volume offered by the floodplain is utilized. Figure 3.6 illustrates the functions of storage and conveyance on the attenuation of flows within a catchment.

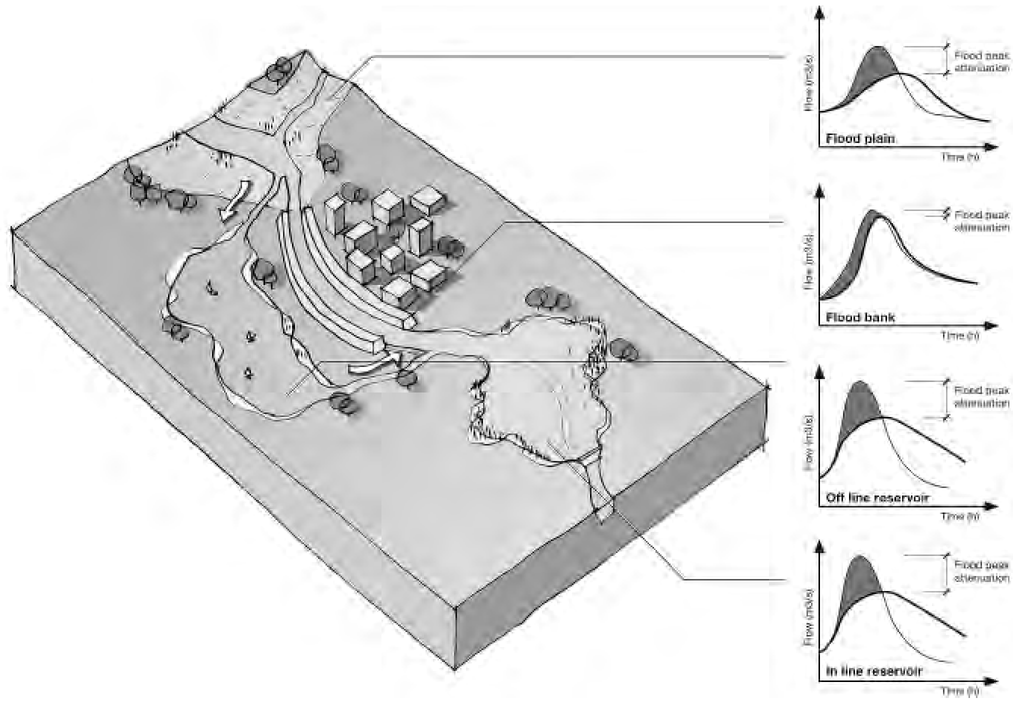

Figure 3.6 Attenuation of conveyance and storage devices within a catchment, Source: Baca Architects

Traditional schemes that have increased the flow-carrying capacity of a river (by decreasing roughness or straightening the course and therefore speeding up the flow) have the opposite effect, in that they reduce attenuation. They may, therefore, decrease flood risk at a particular location, but increase it further downstream. Any scheme that reduces the flooded area at a particular location will, in effect, reduce storage and therefore increases flood risk downstream. A dramatic instance of this was seen in the Mississippi river floods of 2011, as seen in Case study 3.1.

Case Study 3.1: The Mississippi River Floods of 2011

In 2011, for the first time since 1973, the U.S. Army Corps of Engineers, as the US Federal Agency providing flood risk management on the Mississippi River and Tributaries, opened up the Morganza Floodway to relieve flood pressure. Up to 17,000 cubic meters per second can be released from the 125 gates into the floodway, which diverts water from the Mississippi River to reduce flows passing the levees protecting the cities of Baton Rouge and New Orleans. To control the high flows, USACE was forced to breach some upstream levees which resulted in the inundation of farmland and smaller settlements as a means of protecting more densely populated areas (see Photo 3.1). These inundations provided water storage that attenuated (reduced the peak) flows in the main channel..

Photo 3.1: The Morganza Spillway opens to divert water from the Mississippi River, May 19, 2011. Source: FEMA, photo by Daniel Llargues

Flooding is not something new in the region, with the greatest reported flood event occurring as far back as 1927. Large floods also occurred in 1937, 1973, 1993 and 2008. In the spring of 2011, increased water levels in the Mississippi River were caused by the combination of rainfall levels up to four times the normal and unusually high snowfalls in some regions. In addition to these factors, flood risk has also been increased due to urban development in areas that were once farmland. As a result, the hydrolic profile has been altered, causing water to flow quickly into rivers rather than being absorbed by the ground. Professor Nicholas Pinter, who works on flood hydrology at Southern Illinois University, calls this 'hydro-amnesia'. It causes people to build in locations that were flooded in the past and will always have flood risk.

The Morganza Floodway illustrates the successful use of conveyance and storage upstream to divert flooding away from urban areas. It also demonstrates that, even when structural solutions function as planned, there may be downstream consequences which are unpalatable. This is particularly true of systems that are not used very often, and which allow collective amnesia to erode the awareness of risk in the sacrificial areas (in this case, the farmland and homes that were inundated when the levees were breached).

Sources: Lovett 2011; Wynne 2011.

3.3.3. Modification of rivers

Modification of existing rivers may involve engineering procedures which:

- Increase the flow area or alter the line
- Protect the banks from erosion
- Increase the height of banks

The motivation for modification may be to manage flood risk, but it may also be to maintain navigability, reduce bank erosion or facilitate urban development.

Rivers are also modified by maintenance procedures, such as dredging or clearing of vegetation, debris or silt. The main objective here is to preserve the capacity of the channel to carry flood flows, by restoring cross-sectional area or reducing roughness.

3.3.3.1 Increasing the flow area or altering the line

Traditionally, interventions in river channels have been carried out to reduce flood risk at a particular location. This approach has produced artificial river geometries which have often been found, for a variety of reasons, to be unsustainable. A core principle of modern river engineering is that, in general terms, rivers tend to return to their natural ‘regime’ state, in which the main channel has the capacity for a particular flow and no more. While major rivers, especially in developing countries, must be treated as being unique, current thinking is that this flow-rate corresponds roughly to the mean annual flood (Pepper and Rickard, 2009). Greater flow-rates, therefore, are not necessarily contained in the main channel. Artificial deepening of a river channel increases cross-sectional area but may reduce slope; the result can be reduced velocity and increased deposition of silt, tending to a reversal of the initial deepening. Artificial widening may cause deposition close to the river banks. Cutting off a meander will shorten the channel between two points and therefore increase the bed slope; this will increase flow-carrying capacity but will also increase velocities. The result may be erosion of the banks or the bed (termed ‘scouring’) together with deposition further downstream; this will also tend to reverse the initial steepening.

In some circumstances, decreasing roughness or straightening the course may solve local flooding problems, by increasing the capacity of the channel, but a reduction in both storage and attenuation is inevitable. In contrast, where channel naturalization or river restoration includes returning a watercourse to a more natural condition (for example, by reinstating meanders) this can increase storage, enhance the amount of attenuation and thereby reduce flood risk downstream. Photos 3.2 and 3.3 illustrates the contrast in course regimes.

Photos 3.2: Highly channelized red Rouge River Dearbon for flood control purposes source USACE; Photo 3.3 Riverine Wetlands in Northwest Iowa, Source Lynn Betts.

3.3.3.1 Protecting the banks from erosion

Around the world there are many systems of erosion protection, many involving local natural materials and traditional techniques. Bank protection forms part of the local environment and must be appropriate environmentally as well as structurally. Design also involves understanding the scouring potential of the flow. Protection using natural materials may involve establishing vegetation, for example, grasses or shrubs; close to the waterline, reeds or structures made from natural materials, sometimes combined with established vegetation may be used. Wire mesh or open geotextile may be used as erosion protection whilst allowing the establishment of vegetation. Artificial systems include use of gabions, (a basket-like container of mesh or wicker, filled with rocks) stone, concrete blocks, and sheet piling. A revetment is a protective structure with a covering of loose rocks (termed ‘riprap’), gabions or concrete blocks, and an under-layer which provides drainage and protects the base soil from being washed out. However, an alternative approach is to avoid the need for bank protection by re-profiling the bank to a flatter slope, thereby achieving a reduction in velocities (Pepper and Rickard 2009).

3.3.3.1 Increasing the height of banks

Here we consider the physical characteristics of flood walls and flood embankments. Their role, beyond river modification, is further considered in Section 3.10.

Flood walls can be constructed of brick, masonry, concrete or sheet piling. Flood embankments, (also known as levees or dykes) are generally earthen embankments that may have a clay core to reduce seepage; they must be protected from scour where necessary. The height of the wall or embankment must be sufficient to provide the degree of flood protection intended; the strength and stability of the structure must be sufficient to withstand long-lasting pressure of water (for example, if the defense is overtopped). The distance between embankments on opposite sides of a channel has a significant impact on the storage available as water levels rise.

The crest level to which the flood wall or embankment is constructed relates to the probability of the flooding against which defense is being provided. 'Freeboard' is additional height provided to allow for uncertainties and wave effects. Flood walls may form part of the river frontage, such as retaining walls or quays, or can be relatively remote from the river and are solely flood protection structures. The latter may be disguised as landscaped features.

Flood embankments require protection from erosion and scour just as river banks do, as considered above. The typical shape is a trapezium with a flat crest and sloping sides (typically at slopes of between 1:2 and 1:3, vertical to horizontal ratio). Embankments are normally set back from the river edge, both to reduce the risk of erosion and provide storage within the flow area at times of flood. Temporary or demountable flood defenses are covered in 3.10.

Photo 3.4: Labor intensive construction of river flood protection embankments in Bangladesh. Source: Alan Bird

3.3.4. Relief channels

Relief channels are designed to re-direct some of the flow at peak river levels by using an off-take structure (normally a side weir) and a canal to an area where water can be safely discharged without adverse impacts. A 'normally dry' relief channel is at a higher level than the main channel and only carries flow in flood conditions. There may, therefore, be safety issues during sudden flooding as people in the area will have become accustomed to using the area for other purposes (see also Section 3.5.2). A 'normally wet' channel carries some flow at all times, but in both cases there will be a downstream impact of the diverted flow.

In an urban context, floodways act as relief channels and may be a significant component in the 'major' drainage system, as discussed in Case Study 3.2 below and in Section 3.5.

Case Study 3.2: Modernization of the Wroclaw floodway system

Construction of the first components of the Wroclaw floodway system in Poland, one of the largest flood protection systems in Europe started in 2011. The project includes large scale improvements to the system of river channels and flood defenses which provide protection from the floodwaters of the River Odra that flows through Wroclaw. The goal of the project is to reduce the city's flood risk to a probability of less than a 1000-year event.

The city's present floodway system dates to 1923 and has a capacity of approximately 2,400 cubic meters per second, corresponding to a 200-year return period. In 1997, the largest flood event ever recorded in Wroclaw flooded about 35 percent of the city, causing major damage and widespread disruption along the valley of the Odra, this flood was variously estimated as a 1 in 200 to in 1000 year event.

The estimated total flow upstream of the city in this event was over 3,500 cubic meters per second, almost 50 percent greater than the capacity of the city's existing floodway system. Widespread flooding was caused by the breaching and overtopping of the flood defense embankments; in addition a diversion structure to the River Widawa was destroyed, together with the training embankments..

After the floods of 1997, a range of responses to the problem of flooding in Wroclaw, and along the River Odra valley were investigated. Changes in responsibility for flood protection came in 1999 so that the governors of large strong provinces have no reason to wait for central directives. The feasibility study identified a need for the following complementary and interdependent projects mounting to an estimated cost of over $400 million:

- The Bukow Polder completed in 2002 at a cost of $51million
- A 185 million cubic meter on-line flood storage polder (the Raciborz Polder) to be constructed 200 kilometers upstream of the city, this to be extended to 320 million cubic meters once gravel extraction is completed in the area.
- The capacity of the diversion structure and channel to the River Widawa to be increased to 300 cubic meters per second, in combination with improvements to embankments along the River Odra. This will by increasing the conveyance of the channel rather than raising defenses and will require the removal of large amounts of material and bridge widening and strengthening
- Improved forecasting and warning systems

In order to assess the highly complex impacts of each of the proposed improvements, their interaction with each other and with other components of the flood protection scheme, a hydrodynamic computer model of the floodway system has been developed to:

- Test the effect of each component of the project
- Enable 'fine tuning' of the design where necessary
- Understand and allow for the effect of uncertainties in key design parameters.

The models have concluded that the combination of the three measures will be sufficient to manage a 1 in 1000 year flood and protect 2.5 million inhabitants of towns and villages as well as the city of Wroclaw.

The construction of the Raciborz polder would pose a risk of occasional flooding of inhabitants that are concentrated primarily in two villages (240 families). Under Polish regulations, this risk is unacceptable and therefore, the inhabitants are to be moved and the land/property within the polder acquired by the State. This resettlement plan has delayed the completion of the polder.

This example Illustrates the complexity of negotiating a new integrated system of flood control. The defenses have been designed at a catchment level and involve an international water body (the river Oder). A full range of evaluation reports such as EIA and safeguarding reports were required. Structures downstream of Wroclaw have also had to be altered to accommodate extra flow, but areas downstream will also benefit from the increased attenuation in the polders.

Sources: IWPDC 2011; Halcrow n.d.; Faganello and Attewill 2005.

3.3.5. Floodplain restoration

The nature of the development of human settlement in the floodplain of rivers has been identified in Chapter 2 as a major constraint to flood management. Towns and cities have grown and expanded into floodplain areas without consideration of the flood risks involved. Land use zoning and its effective enforcement is a key management tool in trying to prevent such development. Where pressure on land is too great for this, then there is a need to design and construct buildings so that they are able to cope with flooding risks. Also required is an overall management program for floodplain areas, looking at how their former roles as regulators of peak floods can be restored: measures can include remodeling of river banks and the reconnection of former channels that have been built over or blocked.

3.3.6. Reopening culverts

Culverts typically carry flow in a natural stream or urban drainage channel under a road or railway. In some urban areas, the practice of culverting long lengths of a natural watercourse to gain space for urban development has traditionally been widespread. The practice is now generally recognized as having a negative impact on amenity and biodiversity.