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DEVELOPING A HOLISTIC APPROACH TO ASSESSING AND MANAGING COASTAL FLOOD RISK

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2.1 Introduction

Coastal flood systems can be large and complex, and they change with time. These issues create several challenges with gaining a comprehensive understanding of these systems.

Hurricane Katrina in 2005 in New Orleans, USA was one of the costliest coastal flood disasters in history (Seed et al., 2008) and provided several lessons for flood risk management. Key was the lack of a systemic overview of the state of flood defenses prior to the event, mainly due to the size and complexity of both the New Orleans coastal defense system and the responsible organizations. Administrative delineations, especially where the flood system crosses political boundaries that do not recognize the full extent of the natural flood system, are significant constraints to a full understanding of the flood system. A similar lack of overview on emergency response measures and flood defenses led to aggravation of damage during the July 2007 floods in England (Pitt, 2008) and storm Xynthia in France in 2010 (Kolen et al., 2010; Lumbroso & Vinet, 2011). In addition, development contrary to spatial planning laws and a lack of knowledge of potential flood routes within the system caused authorities and inhabitants to be taken by surprise (Kolen et al., 2010).

Coastal flood systems often comprise many land-use types and an equal variety of stakeholders and experts. This is further complicated by interdependencies between the flood system elements. Understanding these interdependencies across the flood system and quantifying their effects on flooding due to changes in the states of particular elements is a significant challenge. A simplified model of the topological relationships allows users to understand effects on the system as particular elements change, or as new or improved information about these elements is obtained.

Changes over time of coastal flood systems include the following aspects that are nonlinearly correlated.

- Climate change
  Global climate change is a key influence on coastal flooding. Global sea levels have risen over the last 100 years and this is expected to continue and accelerate in the next century due to global warming and other possible changes in climate (Church et al., 2013, Church, Woodworth, Aarup, & Wilson, 2010; Nicholls et al., 2014). Any long-term rise in mean sea level will have an effect on extreme levels as it moves the entire distribution of sea levels toward higher values; i.e., it changes the baseline to which the other factors are added (Haigh, Nicholls, & Wells, 2009). Importantly, there is large uncertainty about the magnitude of future change, including other climate change (offshore waves, surges, etc.), although we are confident that sea levels will rise.

- Socioeconomic change
  Changes in coastal population and the coastal economy and resulting change in the use of the coastal zone for infrastructure are key issues for managing flood events. Globally, there has been massive expansion in people and assets at risk in the coastal zone, raising the consequences of flooding (McGranahan, Balk, & Anderson, 2007). This is expected to continue through the twenty-first century (Hanson et al., 2011; Nicholls et al., 2012a), and needs to be considered in risk management.
- Morphological and habitat change
  The coastal system is dynamic and can respond in a number of ways to any external perturbation. For instance, natural coastal habitats such as mangroves and salt-marshes provide protection during flood events, but these are themselves often affected by the same events. Habitat losses affect flooding during subsequent events. Similarly, erosion of beaches is widespread and influences flood risk (Dawson et al., 2009). The challenge here is to capture the flood system in its entirety, including key information on all potential flood routes, including those that may operate under the most extreme conditions over the time-frame of interest.

Historically, responses to reduce negative flood impacts have concentrated on the use of physical defenses to reduce the probability of flooding. More recently, a more holistic emphasis that includes the natural environment and nonstructural measures is considered a more prudent approach to risk management (Renn, 2008; Thorne, Evans, & Penning, 2007). Such an approach embraces the notion of flood resilience and vulnerability reduction as well as prevention (Figure 2.1). Consideration of the flood system beyond traditional flood modeling needs to include the natural environment, the concerns of stakeholders and public groups, information on local risk perception, and existing flood management governance (Figure 2.1, Aven & Renn, 2010, Chapter 5).

In order to overcome the challenges described, such an approach should also be able to integrate information on the different types of elements across the system and provide an overview of the relevant topological relationships and interdependencies. Ultimately this should inform more detailed models to provide a more complete picture of all relevant inputs, as well as the system itself. Establishing a baseline conceptual understanding of the existing flood system from these perspectives provides a logical basis for decision-making and encourages:

- Consideration of the social and political context in which flood events occur;
- The use of the information to develop policies and development controls around current and future development;
- The inclusion of the role of the natural environment both in flood management as well as its intrinsic value, as required in the Habitats Directive (European

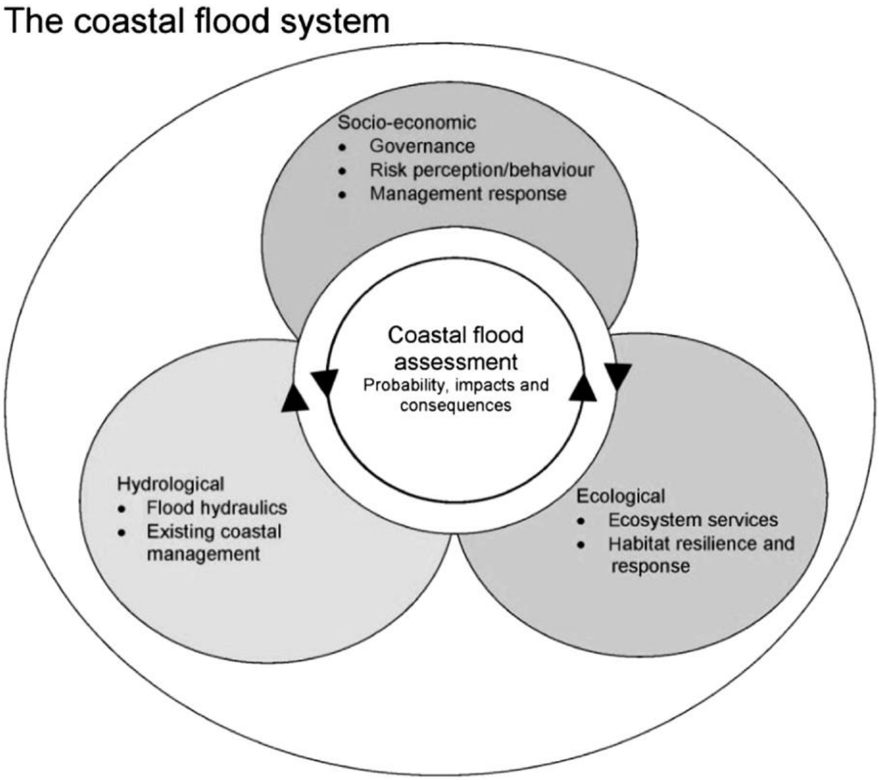


Figure 2.1 The coastal flood system: important aspects for flood assessment and mitigation selection.

Parliament and Council of the European Commission, 2007) and other habitat designations;

- Investigation of the full range of flood-mitigation options across the spectrum of engineering, ecological, and social measures (Chapter 6).

The present chapter looks at coastal floodplains in a systemic sense, including their social and ecological dimensions, and outlines the range of potential flood mitigation measures. This allows Chapters 3–5 to consider in detail a range of innovative engineering, ecological, and socioeconomic mitigation measures, respectively.

2.2 Flood Nomenclature: Vulnerability, Risk, and Resilience

Given the complexity of flooding and flood issues that has already been outlined, a range of concepts and associated terminology is used. In lay discussion these terms are often used interchangeably, providing potential for confusion and miscommunication. Here we lay out a common set of definitions for key terms to facilitate their use and discussion through the book. This draws on earlier work such as the FLOODSite project (http://www.floodsite.net/) and the Netherlands Knowledge for Climate Research Program (http://knowledgeforclimate.climateresearchnetherlands.nl/).

Floods are defined by physical characteristics such as flood depth, extent, and duration, which are fairly transparent. However, there are many systemic concepts such as flood risk, flood vulnerability, and flood resilience which are potentially ambiguous and require definition. All coastal floods begin with a hazardous event, often a storm that produces surges and waves (sources of flooding). However, a source of flooding does not automatically lead to a flood event, as this depends on the pathways and receptors. If the land is high enough, or if it is well protected by dikes and dunes, then the storm does not lead to a flood. However, if the seawater overtops the protection, or breaches the dikes or dunes, than the low-lying land behind it will be subject to flooding with consequences for the associated receptors.

The notion of *vulnerability* is the degree to which a system is susceptible to, and unable to cope with, adverse effects of the change agent, in this case floods. Flood vulnerability is a function of the character and magnitude of flooding and variation to which a system is exposed—the sensitivity and adaptive capacity of that system. A range of flood vulnerability indices have been developed to operationalize this concept (e.g., Balica, Douben, & Wright, 2009). Vulnerability assessment has been conducted in a range of contexts with a view to understand and reduce this vulnerability, including to floods.

The notion of *flood risk* is a combination of probability and consequences, often expressed as an annual mean damage (or consequence) (see Penning-Rowsell et al., 2013). Hence, risk can be expressed as a number, and the units of consequences may be related to flood victims and flood damage to homes, businesses, and nature. To explore the meaning of risk, the four quadrants of probability and consequences can be explored, considering high and low situations. If the probability of a major flood is high and the consequences are high, then this is a ‘‘high’’-risk situation. On the other hand, if the probability of a flood is small and the consequences are small, then this is a ‘‘low’’-risk situation. The situation where floods have a high probability and low consequences is also a ‘‘low’’-risk situation, and with the regular experience of flooding, people and the environment often adjust to such floods, further reducing the consequences. Lastly, there is the situation with low probability of flooding, but with high (very serious) consequences, such as London, the Netherlands, Shanghai, and Tokyo. The challenge in these cases is to reduce the probability of flooding to acceptable levels, and reduce the consequences wherever possible. However, in these situations a failure can be catastrophic, as shown in New Orleans in 2005 (Kates, Colten, Laska, & Leatherman, 2006). Hence while you can calculate risk, the level of risk that we are willing to accept remains a political question.

The notion of *flood resilience* is related to vulnerability and describes the systemic ability to experience flooding with minimum damage and rapid recovery. It can be seen as a design approach that can reduce the damage that occurs due to flooding. For example, it could involve constructing a building in such a way that although floodwater may enter the building, its impact is minimized and recovery is rapid. Resilience operates at multiple scales from individual buildings to communities, towns, and cities. In this more aggregate sense, resilience can be provided by multiple measures that reduce damage and promote recovery, and hybrid approaches can be taken and need to be considered. This might include combinations of warnings, evacuation and emergency plans, land use planning, traditional hard and soft defenses, building construction approaches, provision of insurance, etc.

Reducing vulnerability and flood risk is a key goal of flood risk management, and this can be accomplished in many ways, as discussed later in this chapter and the book as a whole. Enhancing flood resilience is one method for achieving this goal.

2.3 Describing the Coastal Flood System: The Source-Pathway-Receptor-Consequence Model

Risk assessments are used to evaluate and support the selection of appropriate mitigation options for diverse environmental problems including the regulation of hazardous waste sites, industrial chemicals, and pesticides; or the management of ecosystems affected by multiple physical, chemical, or biological stressors (e.g., Arnoldi, 2009). Along Europe's coastlines, the EU Floods Directives requires member states to draw up regularly updated Preliminary Flood Risk Assessments considering potential impacts on human health and life, the environment, cultural heritage, and economic activity. These risk assessments can be used to identify areas at high risk of flooding. Following this, models can be used to produce flood and flood-risk maps for specified events. The development of flood-risk assessments has become an increasingly significant issue over recent years following storm events such as winter storm Xynthia in 2010 (flood damage in excess of V1.2 billion and at least 47 lives lost; Lumbroso & Vinet, 2011), and a recognition that impacts, while initially of local importance, can escalate to have consequences for the wider economy (e.g., Hallegatte, Green, Nicholls, & Corfee-Morlot, 2013). Important examples include the effect of Hurricane Katrina (2005) on global oil prices, and the Bangkok 2011 floods on the global availability of hard drives. As flood risk cannot be eliminated, but only reduced, the management of these risks requires understanding the flood system as it responds to a range of planned and unplanned interventions, (e.g., floodplain development, better defenses) as well as external changes (e.g., climate change). In this way, locally relevant decisions can be made while recognizing other wider or more distant implications.

The management of flood risk also requires fully engaging local communities within the risk-assessment process and making roles and responsibilities explicit, bringing together all the stakeholders in the coastal zone. In this process, it is essential to promote relevant, evidence- and knowledge-based contributions from a range of stakeholders, and to establish a shared understanding of the flood system (Charles, 2012).

This shared vision of the flood system should:

- Address the specific aims of flood management;
- Be accepted by all the disciplines contributing to the flood assessment to ensure integration and transferability of inputs/outputs;
- Illustrate where/how management options are influential in the system;
- Be understandable by stakeholders to enable clear communication of management options;
- Work across different temporal and spatial scales and levels of detail.

This shared view should enable the integration of methods and approaches, both qualitative and quantitative, to promote the understanding of flood events, their impacts, and the opportunities for mitigation measures. Establishing such a shared view before continuing with more detailed analysis is worthwhile, because the debate it engenders helps to develop a balanced view across the different perspectives, which often facilitates successful decisions made later. It also helps to create a common vocabulary, which is a fundamental necessity in integrated flood-risk assessments where the use and interpretation of words varies across scientific disciplines. This process creates a comprehensive picture of the areas of the flood system that are potentially affected by an event, providing useful information for higher levels of analysis. This requires a clear methodological approach, conceptual model, and analytical framework (Robinson, 2008).

Coastal flood risk studies—studies that focus on the evaluation of coastal flood impacts to human assets—conceptualize the coastal floodplain in terms of two components: (1) flood defenses that prevent or reduce the ingress of floodwater and (2) the floodplain behind the defenses comprising all the features considered to be at risk from flooding (Bakewell & Luff, 2008; Burzel et al., 2010; FLOODsite Consortium, 2009; NCDEM 2009). The quantitative evaluation of risk in these studies is usually performed using numerical hydraulic models. The modeling procedure parallels the conceptual description of the floodplains, starting from hydraulic boundary conditions and incorporating the influence of coastal flood defenses in order to evaluate the flood probabilities and damages to specific locations within the floodplain. Related floodplain systems such as habitats or physical coastal systems are often represented as external forces and pressures with little or no consideration of spatial and temporal feedbacks (Verwaest et al., 2008). Hence these treatments are often incomplete.

An alternative, more comprehensive way of visualizing the process of flood risk estimation and all its components is the Source-Pathway-Receptor-Consequence (SPRC) conceptual model (Gouldby & Samuels, 2005). The model was first used in the environmental sciences to describe the propagation of a pollutant from a source, through a conducting pathway, to a potential receptor (Holdgate, 1979). It was first adopted in coastal flooding in the UK by the Foresight: Future Flooding report (Evans et al., 2004). It has subsequently been used in several coastal flood risk studies (Burzel et al., 2010; FLOODsite Consortium, 2009; North Carolina Division of Emergency Management, 2009; THESEUS OD1.15, 2012), and is increasingly underpinning wider flood-risk management. Based on conventional approaches to flood-risk estimation, the SPRC model visualizes flood-risk estimation as a linear process involving a ‘‘Source’’ of flooding, flood ‘‘Pathways,’’ and affected ‘‘Receptors’’ associated with different ‘‘Consequences’’ (Figure 2.2, Table 2.1).

The SPRC model recognizes the principle that the component parts of a system can best be understood in the context of relationships with each other (and with other systems), rather than in isolation. Consequently, it considers flood management within an overall system, highlighting where external drivers can be influential, and—importantly—where system vulnerability can be reduced or exacerbated following intervention. Fundamental to the approach is the defining of relationships between system components at a relevant scale to provide understanding and insight into the flood system under investigation. At its simplest, the concept is a linear representation of a flood event from the Source (of the floodwaters) through the Pathway (route of the floodwaters) to the Receptors (where the water culminates) and calculation of the effect of floodwater on the Receptors (Consequences); see Table 2.1.

The SPRC model presents a snapshot of the floodplain state. This is in turn is driven by boundary conditions operating at a range of spatial and time-scales such as offshore water levels and waves, climate change effects, and human influences such as coastal zone management decisions and actions. Therefore the SPRC model is usually nested within broader approaches such as the Driver-Pressure-State-Impact-Response (DPSIR) framework that conceptualize the influence of pressures and drivers external to the floodplain (e.g., Gregory, Atkins, Burdon, & Elliott, 2013; Kristensen, 2004; Lee, 2013; Zhang & Xue, 2013). The DPSIR assumes cause–effect relationships between interacting components of social, economic, and environmental systems (Carr et al., 2007). By identifying where external factors influence the flood system, the DPSIR framework helps identification of where management interventions (acting as Drivers) influence the Consequences of a flood event. It also illustrates the circular nature of flood management, with an intervention affecting consequences that will influence society’s response, which in turn will determine future management interventions.

Figure 2.3 illustrates that the SPRC model can be divided into two components based on its nesting within the DPSIR: a floodplain state description (SPR) and a

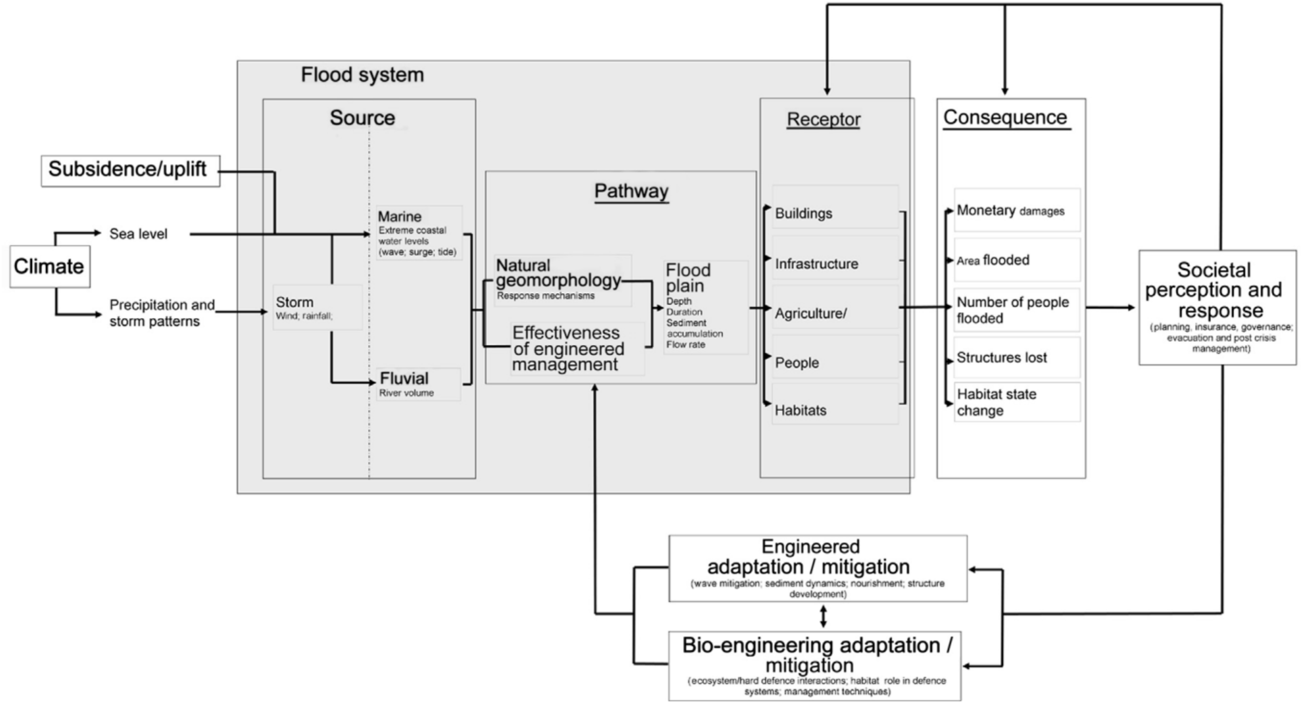


Figure 2.2 SPRC diagram showing where external Drivers can mitigate the Consequences of a flood event at the local scale. *(From Narayan et al., 2014.)*

TABLE 2.1 Definitions and Components of the SPRC Model

Category	Definition	Components
Source	Where the floodwaters originate	Sea: waves, surges, tides, mean sea level River: volume/flow
Pathway	The route for the Source to reach the Receptor	Various land uses seaward of any Receptor, including existing coastal management (e.g., built defenses, nourishment) and habitats
Receptor	Land use and buildings/structures in the floodplain	Urban areas, infrastructure, farmland, habitats, etc.
Consequence	Impact of flooding on the Receptor	Direct/indirect and tangible/ intangible consequences for each Receptor (via various valuation methods)

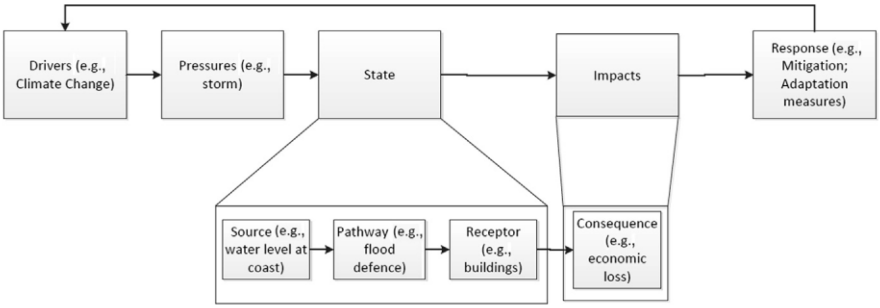


Figure 2.3 Nesting of the SPR-C model within the DSPIR framework. *(From Narayan et al., 2014.)*

description of the consequences to changes in this state (C). Flood risk assessments typically follow this division, using the SPR model to assess flood probabilities of elements within the floodplain and separate economic models to evaluate flood consequences.

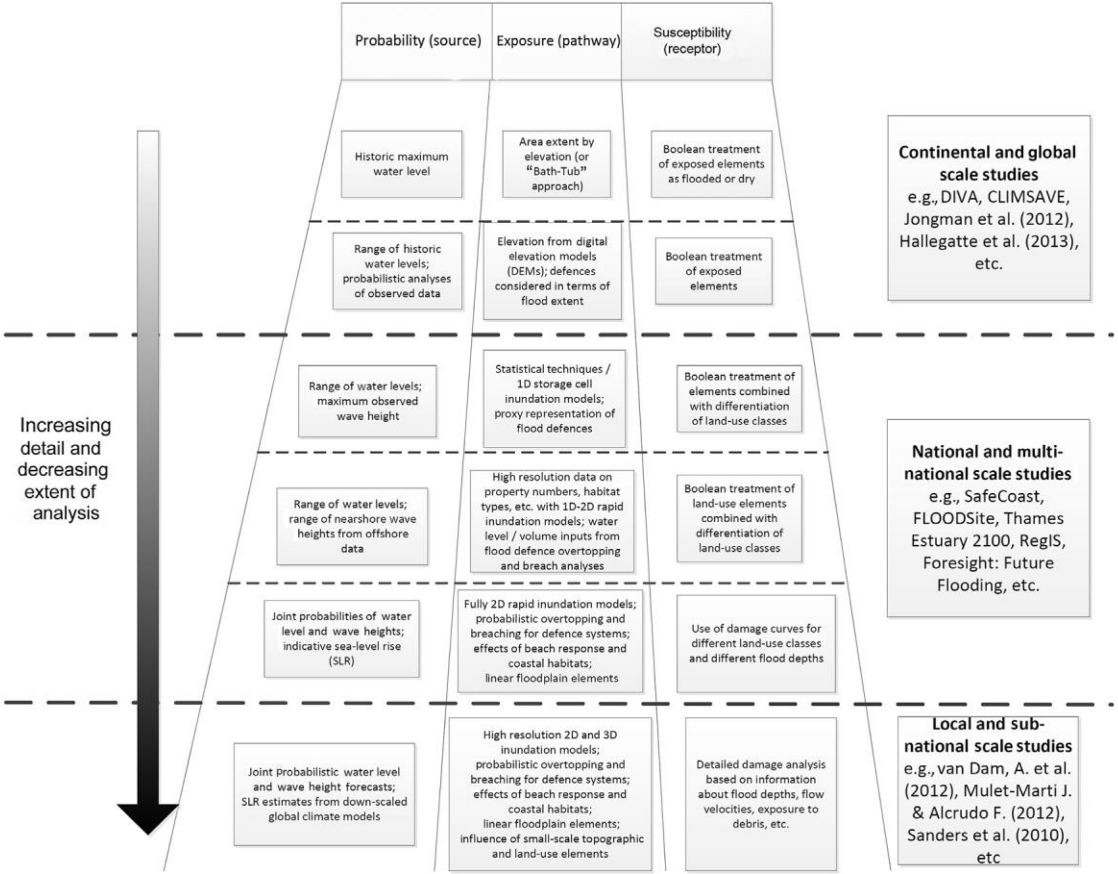
The Source component of the SPR model usually describes the sources of flooding such as waves and water levels. The Pathway component generally refers to all floodplain elements that influence flood propagation within the floodplain. The Receptor component of the model is commonly used to describe the economic cost of a flood event estimated using existing observations and depth-damage relationships (Penning-Rowsell et al., 2013).

It is important to remember here that there may be several Pathways to the same Receptor, and it is useful to identify these in order to fully appreciate potential risk or damages. For example, a house sited in a floodplain directly behind a dyke may appear to be adequately protected, but if a neighboring defense is of a lesser standard (a ‘‘weak link’’) it may fail and the house still flood. Building on the underlying systems approach of the model, mapping of the Receptors and their Pathways encourages the exploration of the wider environmental setting, physical functioning of the site, and spatial variability within the system (Thorne, Evans & Penning-Rowsell, 2007). In this way, the SPRC model offers the opportunity to develop a more comprehensive representation of the flood system, acknowledging the complex network nature of the system (Narayan et al., 2012; Narayan et al., 2014). The mapping also shows that individual elements may be classified as either a Receptor or Pathway depending on the analysis being undertaken and its relative position within the floodplain. This is especially relevant for coastal habitats, which are often considered as Pathways but not as Receptors, which may change as a result of flood events or more continual processes (e.g., sea-level rise).

Though the conventional conceptual model visualizes a linear system of Source, Pathway, and Receptor, in practice a typical flood risk assessment uses a range of diverse models and inputs to describe and analyze the state of the coastal floodplain. Furthermore, the types and nature of models and inputs may differ depending on the scale and extent of detail of a particular assessment.

The key drivers (see Section 2.8.1) affecting the coastal floodplain are (1) climate change, which can affect Sources such as sea level, storm frequency and intensity, and rainfall patterns (increasing or decreasing the extreme water levels during a flood event), and in some cases a non-climate factor: subsidence; (2) sediment supply, which influences Pathways and ecological receptors, coastal geomorphology, and ecosystems; and (3) socioeconomic change, which can alter the type and extent of human receptors within the floodplain (e.g., Thorne, Evans & Penning-Rowsell, 2007). Once the relevant drivers have been determined in any floodplain, the relative importance of each driver can be evaluated based on expert judgment to assess potential impacts on future flood risk. This is based on a score for each driver impact according to its influence on flood risk (altering probability or consequences) under the given driver scenario and time slice (Evans et al., 2004; THESEUS OD1.10, 2012).

Depending on a number of factors, including the scope of the assessment, the relevant drivers and the availability of data and modeling methods, a wide range of numerical models may be used within a flood-risk assessment to describe the state of the coastal floodplain. Figure 2.4 illustrates the possible range and diversity across scales and levels of detail of typical flood-risk assessments, all of which use the linear SPR model described above to conceptualize the coastal floodplain. To ensure the development of a common language and shared understanding of the flood



Probability (source)	Exposure (pathway)	Susceptibility (receptor)	
Historic maximum water level	Area extent by elevation (or "Bath-Tub" approach)	Boolean treatment of exposed elements as flooded or dry	**Continental and global scale studies** e.g., DIVA, CLIMSAVE, Jongman et al. (2012), Hallegatte et al. (2013), etc.
Range of historic water levels; probabilistic analyses of observed data	Elevation from digital elevation models (DEMs); defences considered in terms of flood extent	Boolean treatment of exposed elements	
Range of water levels; maximum observed wave height	Statistical techniques / 1D storage cell inundation models; proxy representation of flood defences	Boolean treatment of elements combined with differentiation of land-use classes	**National and multi-national scale studies** e.g., SafeCoast, FLOODSite, Thames Estuary 2100, RegIS, Foresight: Future Flooding, etc.
Range of water levels; range of nearshore wave heights from offshore data	High resolution data on property numbers, habitat types, etc. with 1D-2D rapid inundation models; water level / volume inputs from flood defence overtopping and breach analyses	Boolean treatment of land-use elements combined with differentiation of land-use classes	
Joint probabilities of water level and wave heights; indicative sea-level rise (SLR)	Fully 2D rapid inundation models; probabilistic overtopping and breaching for defence systems; effects of beach response and coastal habitats; linear floodplain elements	Use of damage curves for different land-use classes and different flood depths	
Joint Probabilistic water level and wave height forecasts; SLR estimates from down-scaled global climate models	High resolution 2D and 3D inundation models; probabilistic overtopping and breaching for defence systems; effects of beach response and coastal habitats; linear floodplain elements; influence of small-scale topographic and land-use elements	Detailed damage analysis based on information about flood depths, flow velocities, exposure to debris, etc.	**Local and sub-national scale studies** e.g., van Dam, A. et al. (2012), Mulet-Marti J. & Alcrudo F. (2012), Sanders et al. (2010), etc

Figure 2.4 Types of flood-risk studies in terms of the SPR model. *(From Narayan et al., 2014.)*

system across all stakeholders before the use of these detailed models, a conceptual description of the flood system is developed via the quasi-2D SPR (Narayan et al., 2014) at the start of the flood risk study.

2.3.1 SPR MAPPING

The quasi-2D SPR model is built in four steps.

Step 1: The landward boundaries of the coastal floodplain system are first decided using a planar water level model for the most extreme water level being considered. This is done under the assumption of a worst-case scenario where complete failure (or absence) of defenses is assumed. This assumption will indicate the full extent of the natural floodplain system and ensure that all system elements are included in subsequent analyses. The seaward boundary of the floodplain system is placed at Mean Low Water Neaps to ensure inclusion of all inter-tidal floodplain elements seaward of the coastline.

Step 2: Once the floodplain boundaries are defined, all floodplain elements, including flood defenses, are mapped as unique entities classified based on land use. This provides a platform for future integration of any analysis with the socioeconomic aspects of a flood event, such as economic consequences or land-use planning scenarios.

Step 3: Next the relationships between the identified elements are defined. A link is identified between any two elements if the elements share a geographical boundary, including engineered flood defenses. Flood compartments created by these defenses can therefore be studied as part of the larger natural floodplain system, rather than as isolated subsystems. The elements and links are then schematized to a systems map. The move from a geographical map to a systems map allows easy, rapid, and comprehensive analyses of the topological relationships between different elements regardless of their location or size.

Step 4: Once the system diagram is built, the sources of flooding are identified on all boundaries and, if necessary, within the system boundaries. These sources are also schematized, and all links between them and directly connected system elements are identified.

The mapping process and resultant SPR maps (see Chapter 7) represent the components and linkages within the flood system in a defined space, without scaling or topographical constraints. Spatial limits for the SPR mapping need to be clearly defined considering the geomorphological setting of the site and an upper elevation of the area should be defined, e.g., set above current flood levels (allowing for sea-level rise). This sets the boundary for any information that needs to be collected in the flood-risk assessment. This ensures that the SPR analysis extends beyond any expected flood extents within the mid- to long-term (e.g., 50–100 years). For sites that extend over large areas, a hierarchical SPR approach can be useful, allowing a detailed analysis to be carried out in areas of interest, while recognizing the wider context (Monbaliu et al., 2014; Villatoro et al., 2014, Chapter 7).

Once developed, the SPR maps provide a comprehensive characterization of the coastal flood system network that can be interpreted and analyzed in a number of ways. Key aspects include (1) the potential for multiple potential flood routes to particular Receptors (e.g., the Gironde estuary case-study; Monbaliu et al., 2014); (2) areas where reliance on existing coastal defense structures is notable; (3) the most beneficial locations for new or upgraded defenses; or (4) where land use may be modified. The identification of existing management can also identify routes for floodwaters that are not directly related to coastal mitigation measures but to urban management and flooding (such as storm drains, culverts, or sewers). The application of a system mapping process provides an inexpensive but rigorous and comprehensive model of the coastal flood system, essential not just for understanding these systems but also for defining the system components of analysis for the more detailed assessment required as part of flood-risk assessments.

Following the SPR mapping, an improved baseline suitable for the modeling of flood events is created. This commonly requires a base layer of digital topography and land use that can then be used to generate flood and erosion maps and estimate economic damages and potential human losses. Consequently, the use of a Geographic Information System (GIS) approach to capture, manipulate, process, and display spatial or geo-referenced data is beneficial (see Rodriguez, Montoya, Sanchez, & Carreno, 2009, and Chapter 6).

2.3.2 Defining the Sources in the Coastal System

Sources are essentially classified into three groups according to flood duration: short-term (storm surge, wind waves, tides, runoff due to downpours); seasonal (river high/low waters); and long-term processes (sea-level rise, local land surface vertical movement). Historical analysis (long and homogeneous time series of water levels or discharges) can be used to establish existing return periods for different extreme events. Extreme water levels from the sea are caused by a combination of several factors: (1) high astronomical tides due to the sun and the moon, (2) storm surges due to high winds and low atmospheric pressure, and (3) waves caused by local high winds or far-traveled swell from oceanic fetches. Hence, tropical or extra-tropical storms can both produce extreme sea levels and cause flooding. Changes in any of these factors may alter the characteristics of a flood event. Historically, the long-term change in mean sea level has contributed to changing extreme sea levels, and globally this is increasing the frequency of high sea levels (Menéndez & Woodworth, 2010).

Understanding extreme sea levels involves an analysis of the above components, including questions of statistical dependence and independence (e.g., Haigh, Nicholls, & Wells, 2010). Often such time series are unavailable, are not of the required length or suffer from data inhomogeneity such as problems related to changing instrumental accuracy, observational practices, analysis routines, etc. (WASA-Group, 1998; Weisse & Von Storch, 2009). This may lead to incorrect inferences unless properly addressed. Alternatively, a number of re-analyses, hindcasts, and downscaling activities can be used, in particular for tide surge and wave conditions: e.g., PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects, http://prudence.dmi.dk/) or HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe, http://www.mar.ist.utl.pt/hipocas/). The resultant local estimates of extreme sea levels and wave climate can be used to specify the environmental loading conditions on the coastal defenses.

2.3.3 Defining Pathways in the Coastal System

Pathways are the routes and processes that are active during a flood event and transport floodwaters from a source to a receptor. Thus, without a Pathway, a flood event cannot have any Consequences. On many occasions, an individual Pathway may have multiple Receptors, and individual Receptors may have multiple Pathways. As Pathways include the components of the flood system (identified in the SPR mapping) through or over which floodwaters flow, they can capture the different defense failure mechanisms, such as overtopping versus breaching, which can produce different flooding patterns. Pathways can be also receptors. Coastal structures (Chapter 3) affect the flood extent and they can stop flooding, fail or be degraded by the intensity of the Sources, and act as a Pathway (see also Section 6.2.1). Similarly, coastal habitats (see Chapter 4) may be regarded as Pathways as far as they offer some coastal protection in terms of wave energy reduction or increased beach stability (e.g., biogenic reefs, dunes), and of course they are also Receptors whose survival or modification depends on the Sources.

2.3.4 Defining Receptors in the Coastal System

Receptors are usually defined by either what can be found on, the use of, or the intrinsic value of the land that has the potential to flood. They are mainly, although not exclusively, found above the lowest water level for the site and can form part of either the human or natural system. The initial information for the identification of potential Receptors is generally land use, supplemented with more detailed habitat mapping and additional socioeconomic information. An example of a broad-scale receptor classification is shown in Table 2.2.

Consequences may be specific to the identified Receptor: e.g., for habitats, the area lost and species change due to flood duration; or more general: e.g., for

TABLE 2.2 Example Broad-Scale Classification of Receptors

System	Receptor Classification	Land Use Examples
Human	Buildings (residential) Buildings (nonresidential) Infrastructure Agriculture Mariculture	Houses Factories, storage facilities Roads, hospitals, airport Arable land, grazing Mussel farming, fish farms, oyster beds
Natural	Natural element Habitat	Beach, spit, salt marsh, mudflat Dune, salt marsh, kelp beds

buildings/infrastructure, the damages based on depth-damage curves, number of people flooded, number of houses flooded, etc. Analysis of the Pathways and Receptors of a flood system, enshrined by existing flood management regimes, is discussed in Section 2.4.

2.3.5 Defining Consequences in the Coastal System

The development of the SPR mapping encourages the identification of direct Consequences of flooding related to the nature of the Receptor(s). The mapping of the consequences of a flood event is usually done after quantifying the flood probability of the different parts of the floodplain, as described in Figure 2.3. The process—and probability—of flooding is driven by the physical state of the flood pathways. However, the consequence of a flood event is felt only by an element that functions as a Receptor—even though this element may also function as a flood Pathway. For instance, the flooding of a beach, apart from acting as a flood Pathway, may result in tangible economic losses to the local tourist industry. Some floodplain elements may function primarily as Receptors. For instance, critical infrastructure such as hospital buildings are elements for which the consequence of flooding is of immediate concern. Consideration of the Pathway effect of the building will depend on the detail and sophistication of the data and numerical models used for later analysis (see Figure 2.4). On the other hand, the flooding of infrastructure such as a pumping station will be of relevance both for flood propagation (as a Pathway) as well as in terms of the direct economic costs of replacing damaged parts (Receptor–Consequence). A first overview of typical classes of Receptors and their associated consequences for a flood event is given in Table 2.3. Once the physical characteristics of a flood event (i.e., flood extents, depths, probabilities) are mapped onto to the floodplain system description, these can be combined with information on depth-damage curves and cost estimates for specific Receptor types (Zanuttigh et al., 2014; Sections 6.6 and 7.6) to obtain the

TABLE 2.3 Example of Direct Consequences of Flooding Associated with Receptors

Receptor	Example of Direct Consequences
ALL	Area permanently flooded (land loss) Area temporarily flooded/displaced
(Critical) infrastructure	Physical flood damage
Buildings—residential	People temporarily flooded Building/content damage
Buildings—commercial/industrial	Area temporarily flooded Building/content damage
Habitat	Habitat state change
Agriculture	Flood damage to crops Change of agricultural practices (e.g., crops to pastoral)
Recreation	Flood damage to recreational facilities

consequences of a flood event. Analysis of the consequences of a flood event is described further in Section 2.5.

2.4 Assessment of Existing Flood Management

Analysis of present conditions, including existing defenses, policies, regulations, and governance arrangements (Chapter 6), is an essential part of the flood risk assessment process (Penning-Rowsell et al., 2014). It provides the background against which any future management options will be taken and identifies those responsible for implementing such a strategy. Including those involved in policy development or decision-making also offers the opportunity to more fully integrate science into policy (de Vries et al., 2011).

Surveys can be used to characterize the risk governance in coastal floodplains based on five ‘‘building blocks’’:

- Administrative organization of coastal management;
- Legal system;
- Financing system;
- Economy of intervention measures;
- Participation level of stakeholders.

Many sites have complex institutional structures for flood management, with responsibilities found at local, regional, and national, as well as international, levels. This information will need to be collected in a systematic manner from local policymakers, managerial authorities, and administrators. Presenting the conceptual model of the flood system (Section 2.3) is often a beneficial aid to these discussions. Experience within the THESEUS project showed that institutional culture, traditions, and capabilities are of great significance to (innovation in) risk management, and could be of at least the same importance as technical issues in risk assessment and reduction choices (THESEUS OD4.8, 2013).

Existing management structures, flood policies, and defense design often reflect the relative importance and current understanding of coastal flooding and its consequences in any floodplain area (Aven & Renn, 2010, Chapter 5). Legal obligations, frequency of occurrence, economic value of the protected area, and previous experience with flood events are all influential. Where the flood risk is considered greater than other risks, in Europe there is often a strong tendency to focus on the reduction of the probability of flooding using physical coastal defenses and/or nourishment schemes (Chapter 3). Conversely, where flood risk is considered as one of many risks, the range of flood management options examined is often wider. In other regions, risk reduction may have other foci: for instance, in the USA there is focus on building standards and raising the levels of buildings above flood levels.

Stakeholder interviews are probably the most appropriate methods to identify the current governance structures (de Vries et al., 2011). Such interviews could be supported with the help of a structured or semi-structured questionnaire, which should be sent in advance to the interviewees. An additional benefit of undertaking group interviews is that they can bring together, sometimes for the first time, stakeholders with management responsibilities in the coastal zone. Possible feedback to participants of the resulting report is essential, particularly where there may be ethical issues or wider implications in the accumulation of the information.

The experience in the THESEUS study sites across Europe (Penning-Rowsell et al., 2014, Chapter 7) shows that the institutional arrangements in many coastal situations are complicated, almost invariably multilevel, and potentially confusing to the public. Central government is almost always involved, because of the large investment required for engineering mitigation works to reduce risks from flooding and their involvement in spatial planning legislation at the coast. It is recognized that these investments and powers cannot simply come from the communities at risk, but need support from the general taxpayers and national or regional-level legislators. Further, in most of the sites there is a provision for sustainable coastal zone management, within the existing legislation. However, not all laws and regulations are properly enforced. Outside Europe, these factors will require further assessment, as this model may not apply.

2.5 Flood Damage

Flood damage is defined as all the varieties of harm provoked by flooding. It includes all detrimental effects on people, their health, and properties; on public and private infrastructure, ecological systems, cultural heritage, and economic activities (Messner & Meyer, 2006). Understanding the nature of flood damage is important in assessing flood risk. For most people, the benefits of flood risk reduction at the coast is the direct flood damage on property and economic activity avoided as a result of schemes to reduce either the frequency or impact of flooding (Penning-Rowsell et al., 2013). However, the consequences of flooding for people are more complex. Following Smith and Ward (1998), we can classify flood losses into direct and indirect losses. Direct losses are caused by the physical contact of the floodwater with humans, property, or other objects, and the location of the flood will indirectly affect networks and social activities, causing indirect losses (e.g., disruptions of traffic, trade, and public services). Further, we can distinguish between immediate or long-term consequences and tangible or intangible consequences. Such consequences depend on the land uses found within the floodplain. Immediate impacts of flooding can include loss of human life, damage to property and infrastructure, and destruction of crops and livestock. Examples of long-term impacts include the interruption to communication networks and critical infrastructure (such as power plants, roads, hospitals, etc.) that can have significant impacts on social and economic activities. More difficult to assess are the intangible impacts; for example, the psychological effects of loss of life, displacement, and property damage can be long-lasting (see Table 2.4). Methods of assessing these impacts are equally varied. They range from quantitative (financial or economic) to more qualitative approaches (see Chapter 6).

A key concept in flood-loss estimation is the concept of damage functions or loss functions. They relate damage for a specific element at risk to the features of the flooding. These functions are similar to dose–response functions or fragility curves in other fields (Merz Kreibich, Schwarze, & Thieken, 2010; Penning-Rowsell et al., 2013). Flood damage losses are a function of the nature and extent of the flooding, including its duration, velocity, and the contamination of the floodwaters by sewage and other pollutants. It is important to ensure that for the purposes of flood-risk management there is consistency in the assessment of damages: this often means that only the national economic losses caused by floods and coastal erosion are assessed, rather than the financial losses to individuals and organizations affected, severe though those may be.

Protecting property from flooding is considered in investment decision-making through approaches such as cost–benefit tests that, for example, the UK Treasury uses, and which are becoming more commonly applied throughout the world. Also environments are often now protecteddsometimes irrespective of costdcourtesy of national and European legislation (creating Ramsar sites, Special Protection Areas, Sites of Special Scientific Interest, etc.). Nevertheless, the ‘‘social’’ effects of floods need to be considered: those caused by the disruption of people and communities that do not or cannot carry a monetary price tag. Floods can cause health impacts that are enduring, including the stress and trauma created months or years afterward

TABLE 2.4 A Typology of Flood Losses with Examples

		Measurement	
		Tangible	Intangible
Forms of flood losses	Direct	■ Damage to private buildings and contents ■ Destruction of infrastructure such as roads and railroads ■ Erosion of agricultural soil, destruction of harvest ■ Damage to livestock ■ Evacuation and rescue measures ■ Business interruption inside the flooded area ■ Clean-up costs	■ Loss of life, injuries, loss of memorabilia ■ Psychological distress, damage to cultural heritage ■ Negative effects on habitats/ecosystems
	Indirect	■ Disruption of public services outside the flooded area ■ Induced production losses to companies outside the flooded area (e.g., suppliers of flooded companies) ■ Cost of traffic disruption ■ Loss of tax revenue due to migration of companies in the aftermath of floods	■ Inconvenience of post-flood recovery ■ Trauma ■ Loss of trust in authorities

Source: Adapted from Merz, Kreibich, Schwarze, and Thieken (2010) whenever floods threaten to reoccur. Loss of treasured possessions in floods can be heartbreaking, and much more significant than financial losses, which are now commonly recovered through government compensation schemes or household insurance policies. These impacts are seen as the net effect of the threat, the mediating influences (e.g., flood defenses) that moderate that threat for the affected population, and the support capacity in households, communities, and indeed the nation that helps to promote resilience in that population and the capacity to recover from the threat, the event, and its effects. In this respect, the health and mental health effects of flooding need to be considered, so that these can be accounted when evaluating policy options at the coast.

Natural disasters such as flooding can affect people's health in a number of ways (Tapsell, Penning-Rowsell, Tunstall, & Wilson, 2002); good health being defined as complete physical, mental, and social well-being. Many impacts are associated with the trauma of flooding and living subsequently for long periods in damp and dirty conditions. The close proximity of people living in cramped conditions in their homes following flooding mean that some of these adverse health effects can be passed from person to person within the household, particularly where pre-existing health issues are present. Hence, the effects of flooding on people's health and general well-being can continue for many months after the actual flood event. People suffer from psychological health impacts from the stress of the flooding (Tapsell, Penning-Rowsell, Tunstall, & Wilson, 2002). Stress arises from the difference between the perceived demand the event places upon the individual and the resources the individual can draw upon to adapt to that demand. The severity of the impact represents the degree to which coping and support capacity are insufficient to cope with the challenge and costs of responding.

The conclusion is that the impacts of flooding on people are more extensive and complex than have hitherto been appreciated. Hence, assessments of the effect of flood risk reduction measures on these more intangible impacts are flawed and incomplete if only monetary losses are used within the necessary project-appraisal and option analysis methods.

2.6 The Social Context of Flooding at the Coast

The social context of floods is a critical dimension of any system-based analysis of floods. All human groups are not equal when facing floods, and within coastal communities parts of the population may be more vulnerable to floods and their consequences. A review of social vulnerability analysis to floods indicates that the following key dimensions must be taken into account: demographics (age, population density, migratory status), wealth (absolute and its distribution), health status, and mobility. McElwee (2010), Baum, Horton, & Choy (2008) and Coninx & Bachus

TABLE 2.5 Benefits and Limitations of Qualitative Assessment Methods

Techniques	Structured Interviews, Focus Groups, Surveys, Questionnaires
Benefits	Engage stakeholders in the flood-management process Provide depth, detail, and context for more quantitative approaches Ensure identification and focus on relevant issues for stakeholders Identify people's individual experiences, building up a picture of the diversity of stakeholders' views and why these exist Attempt to avoid pre-judgments, identifies trends and emergent themes Can be cyclical, with analysis informing subsequent data collection and further analysis Focus groups promote openness by allowing different views to be expressed
Limitations	Identification of relevant individuals Time consuming; available time may dictate number of participants, length of interviews, and analysis Not easy to generalize or systematically compare a small number of interviews Highly dependent on skills of the interviewer

(2007) provide detailed examples for Vietnam, the Gold Coast (Australia), and climate change, respectively. Social vulnerability is a complex phenomenon, and no single measure comprehensively includes all aspects of vulnerability (Adger, Hughes, Folke, Carpenter, & Rockstrom, 2005). Factors such as those listed above can all be considered, but vulnerability is site-specific and some relationships between social characteristics and vulnerability are unlikely to be linear or readily transferable. While there seems to be a consensus on the dimensions to be taken into account, their local articulation varies because of local variation in governance, cultures, and perceptions, and this requires evaluation in any assessment.

A review of governance structures and perceptions should thus take place at the beginning of any flood risk assessment, and the stakeholders contacted should be encouraged to participate throughout the assessment process (Section 2.4, Chapter 5). Information is generally collected from stakeholders using qualitative methodologies: individual interviews, semi-structured interviews, and focus groups. These are time-consuming processes to apply, with distinct benefits and limitations (Table 2.5). Ultimately, a focus on the participation of local communities and authorities has two major benefits:

- Optimal use is made of the know-how and skills of local communities, taking into account their wishes and needs;
- The involvement and shared responsibility of local parties in coastal risk assessment will guarantee a sound community basis for the development of management plans (Chapter 6).

Recently, the Social Vulnerability Index has been suggested as a comparative spatial assessment of human-induced vulnerability to environmental hazards (Cutter

Boruff, & Shirley, 2003; Wisner et al., 2004). This index is based on a large set of measurable variables that can be grouped into main common factors such as population structure, gender, income, socioeconomic status, and renters (www.csc.noaa.gov/slr). Analysis and mapping of social vulnerability should also consider identifying critical facilities or resources to help prioritize potential hazard mitigation.

2.7 Coastal Habitats Within the Flood System

Healthy and productive environments are the basis of sustainable development and human welfare, providing both direct resources and key ecosystem services such as coastal defense (Millenium Ecosystem Assessment, 2005). Over the last few decades there has been a growing recognition of the importance of coastal ecosystems for their biodiversity and aesthetic value, and regulations are increasingly being implemented to promote their conservation across the world (e.g., European Commission, 1992; Nicholls et al., 2012a). However, one aspect of the flood system that is not always fully recognized by coastal managers and stakeholders is the role of coastal habitats in determining the impacts of flood events (Jones et al., 2011, pp. 411–458).

In general, coastal habitats can tolerate a degree of flooding by sea water, and are able to adjust in accordance with both short- and long-term processes if there is the required space and sedimentary material to do so. Short-term and seasonal processes are part of the dynamic coastal environment. For example, a salt marsh requires flooding on a daily basis, while the erosion and deposition of sediment driven by coastal processes is part of a dynamic sand dune system. However, coastal grasslands are not tolerant to flooding, but are able to regenerate after temporary flooding through the soil seed bank (Kalamees & Zobel, 2002). If coastal flooding becomes more regular, there is likely to be a change in the species composition of coastal grasslands. If water inundation occurs as a result of long-term processes (e.g., sea level rise), it is assumed that this is permanent. Unless defended, this will result in the loss of terrestrial habitat areas, although it is important to recognize that intertidal/subtidal habitats will be gained. If habitats have the ability to ‘‘retreat’’ (the affected terrestrial habitats can move landward), these newly occupied territories may be considered as additional coastal habitat. Alternatively, where there is no possibility for habitat retreat because of natural or anthropogenic barriers (e.g., cliffs or sea walls/dikes), areas of lost habitat cannot be compensated. Overall there is a need for understanding of the possible effects of changing inundation duration on any coastal habitat.

Within ecology, vulnerability is considered to relate to the inherent properties of an ecosystem that determine resistance and resilience to any perturbation. An ecosystem can be defined as resistant if it has a high ability to withstand disturbance events. For example, resistance can be measured in a salt marsh as the biomass lost or anticipated to be lost as a consequence of equal disturbance events. However, once a system is damaged by a flood or storm event, the system is more vulnerable to greater damage by a second flooding event even if this second event is of lower magnitude. Resilience, on the other hand, is the time the ecosystem needs to recover to the state from before the disturbance event took place. Resilience can be measured as the recovery time. Hence, more vulnerable ecosystems are less resistant against a disturbance event, or resilient with longer recovery times. Therefore, the most vulnerable ecosystems have both low resistance and resilience, and the persistence of such systems is unlikely.

2.8 The Physical Context of Flooding at the Coast

2.8.1 EXTREME WATER LEVELS

As explained in Section 2.3.2, extreme water levels from the sea are caused by a combination of several factors: high astronomical tides, storm surges, and waves. Changes in any of these factors may change the magnitude and impact of a flood event. Long-term changes in relative mean sea level have also contributed to changing extreme sea levels: globally this is the most relevant factor for changing extreme water levels (Menéndez & Woodworth, 2010). For some coastal areas (deltas, estuaries, bays, and inlets), river input can also influence flooding, particularly when high flows coincide with extreme coastal conditions (e.g., Gilbert & Horner, 1984, p. 216; Monbaliu et al., 2014). Local effects from water works, land subsidence, gas extraction, etc. may also be substantial, and where this is the case should be considered. This is particularly a problem on recent alluvial sediments and on deltas, such as widely found in South, South-East and East Asia (Nicholls et al., 2014). Consequently any coastal hazard assessment should first aim at identifying processes potentially relevant at the local scale and subsequently at estimating their variability and their past and potential future contributions to extreme water-level changes. In many cases, the most important factors comprise hydrology; effects from water works and engineering; coastal ocean conditions such as mean sea level, waves, and storm surges; and river flow and subsidence. A combination of statistical analyses of existing data, together with modeling studies, represents the most commonly used approach.

2.8.2 COASTAL MORPHOLOGY

Long term morphological transformations are to be expected in coastal areas as a result of gradients in long-term sediment transport, sea level rise, and changes of the environmental dynamics (Cowell et al., 2003; Nicholls et al., 2012b, 15 pp; Stive, Cowell, & Nicholls, 2009, pp. 158–179). How the coastline will respond in the future depends not only on the complex physical processes involved in the hydrodynamics and morphodynamics of coastal regions but also on the interactions between the physical environment and anthropogenic actions. Furthering our understanding of morphological change will improve the management of coastal flooding in the future, as we anticipate future adverse conditions.

Morphological change can be rapid, being induced by tsunamis (e.g., Japan, Tanaka et al., 2012, and Chile, Morton, Gelfenbaum, Buckley, & Richmond, 2011), rainfall (e.g., landslides in Canada, Guthrie, Mitchell, Lanquaye-Opoku, & Evans, 2010), and storms (e.g., Hurricane Wilma in Cancun, Mexico, Silva et al., 2012), Hurricane Sandy in eastern USA (Trembanis et al., 2013); or can be caused by gradual stresses, generated by a deficit in sediment supply, either due to long-term reductions or temporary inequalities (e.g., Varna, Bulgaria, Villatoro et al., 2014), seasonal changes in wave climate (e.g., modifications of the profile and plan shape in beaches in Wales, Thomas, et al., 2010), drift inequalities (e.g., in the South of Spain, Moreno et al., 2010), and, finally, by longer-term changes in climate (sea level change and human activities).

According to Stive et al. (2002), Cooper (2009, pp. 129–152), and Oumeraci (2004), coastline changes take place at a variety of temporal and spatial scales, and proper understanding of coastal behavior requires that short-term patterns of change be placed in a longer-term perspective. The cumulative effects of a change at any time-scale are normally nonlinear, dynamic, complex, and sensitive to anthropogenic interference and climate variability, and hence are subject to large uncertainties. The impact of high-magnitude, low-frequency events, such as those mentioned above, may also be important. In terms of coastal morphology, coastal managers need to be aware of obvious, visible features such as foreshore slope, the width and height of the berm, and the backshore width. Other features, controlled by the geological setting or underlying topography of the area, must also be considered. In addition, a checklist for the factors to be taken into consideration should include sediment type (grain diameter, form, sorting, mineral composition, moisture content, stratification (e.g., Camenen, 2007; Alcerreca et al., 2013), sediment volume, and supply. Climatic and oceanographic settings also form part of the analysis (waves: height, period, and angle; tides: range, diurnal pattern, and stage; currents: velocity and direction; and winds: velocity and direction). Given the inherently low predictability level and the broad range of time and space scales of these processes, monitoring is strongly recommended (Nicholls, Townend, Bradbury, Ramsbottom, & Day, 2013).

The key processes involved in coastal morphological changes are a loop of erosion, transport, storage, and deposition of sediment. Coastal erosion, which can be understood as land loss, landward movement of the shoreline, or a reduction in beach volume, is most likely to cause coastal flooding due to climate change. In some areas, in addition to the effects of climate change on coastal morphology, local erosion processes, and coastal squeeze must also be considered. The term ‘‘coastal squeeze’’ is used to describe the retreat of the shoreline in areas where landward retreat of the geomorphic feature is not possible, ‘‘squeezing’’ the width of the coast and its protective function. The urbanization of coastal areas has turned coastal erosion from a natural phenomenon into an urgent problem of growing intensity in many areas around the world. Dynamic ecosystems and their undeveloped coastal landscapes are gradually disappearing, due to a lack of space and sediment, (Cooper, 2009, pp. 129–152).

While natural erosion may have a short-term (temporary) or long-term (chronic) character, man-made erosion generally has a chronic character. For this reason, before undertaking any action to protect an area from the effects of erosion, coastal managers must first identify and understand which type of erosion (temporary or chronic) occurs (Eurosion, 2004). Some examples are presented in Chapter 7 of this book. A systematic cataloging is therefore needed which not only accounts for the effects of erosion but also for the main causes, for the relevant time and space scale, and for the order of magnitude of recession at the site under consideration. This is a prerequisite to deciding what action to take: protection against wave attack, increasing dune sediment storage, or fixing the shoreline and/or infrastructure protection (e.g., Mendoza et al., 2014 and Chapter 3 show innovative cases). In the case of chronic erosion, improving the protective role of natural structures may also be implemented.

Presently, numerical modeling is the means most often used to predict long-term morpho-dynamical changes. The available numerical models are not completely satisfactory and are subject to uncertainties from diverse sources. Therefore, we need to account for the inherent stochastic variability of the influencing parameters, modeling errors, and also human and organizational errors (Oumeraci, 2004), as well as focusing attention on new methods as they emerge.

Most numerical models are integrated by hydrodynamic, sediment transport, and morphological modules. It is necessary to have field measurements and observations to calibrate and to validate the models. Since the models do not directly consider the interaction between hydrodynamics and sediment transport, an update loop is required to account for the influence of morphological change on the hydrodynamics and sediment transport. Specific modeling methods (see Chapter 7 of this book) are needed to predict the response of the coastline at different scales. These methods come with varying levels of reliability, accuracy, and required expertise, and may be seen basically as process-based numerical models, behavior-based numerical models, statistical analyses, geomorphological analyses, parametric equilibrium models, and other, emerging techniques (Sutherland, 2007).

The future geomorphic evolution of coastal areas is heavily dependent on many factors that are difficult to consider, such as the relation between the physical and biological characteristics of ecosystems and their resilience, among others. Therefore, the use and protection of coastal zones will always be subject to conflict and compromise. We need to take into account the evolving socioeconomic demands, impacts of human interventions, and morphological changes. Hence, engineering solutions have to deal with each case individually.

2.8.3 DEFENSE FAILURE

On defended coasts, flooding arises when defenses fail in some way. Three separate mechanisms of such failure can be considered: overflow, overtopping, and breaching. In these mechanisms, still water levels can flow over (overflow), wave action propels water over the crest (overtopping), or the defense is lowered (breaching). Few defenses remain undamaged under heavy overtopping, and this can initiate a breaching responsedhence one type of failure can lead progressively to another. Failure to close flood gates, mobile barriers, and sluices can also allow flooding: these are mainly caused by errors in human operation. As already noted, natural geomorphic and habitat features may directly or indirectly provide flood protection. For instance, beaches and dunes can attenuate wave affects prior to contact with structural defenses, or act as a line of defense in their own right; while offshore barriers, breakwaters, reefs, salt marshes, and mudflats may dissipate wave energy further away from the floodplain. In general terms, we wish to minimise defense failures and avoid breaching as the volume of water that passes on to the floodplain can increase by several orders of magnitude, greatly increasing the consequences of any flood. This topic is considered in more detail by Kortenhaus (2012). Of course defense failure should be accounted for when planning coastal management and assessing its performance (see Section 6.2.1).

2.8.4 MODELING FLOOD EVENTS

There are numerous hydrodynamic models that can be used to simulate the propagation of floodwater across floodplain areas. These models generally solve a form of the two-dimensional shallow water equations and range in complexity from raster-based approaches (Bates & De Roo, 2000; Bates et al., 2005, 2010; Bradbrook Lane, Waller, & Bates, 2004; Dottori and Todini, 2011) to more complex finite volume approaches (Lane & Richards, 1998) that solve the full two-dimensional equations.

The accurate representation of the complex dynamics of sea–river interaction and/or beach reshaping and run-up requires a three-dimensional solution of the three-dimensional Reynolds-averaged Navier Stokes equations (RANS equations). This in turn necessitates of an approximate numerical technique such as finite differences, finite elements, or finite volumes. A number of codes are available for local predictions of three-dimensional velocity fields in main channels and floodplains, such as MATO-3D (Posada, Silva, & de Brye, 2008) and FLUENT. However, these approaches are computationally expensive (run time of several days) and thus far have only been applied to channels of a limited domain size and regular geometry (Woodhead, 2007).

Two-dimensional approaches typically use depth-averaged velocity obtained by integrating the Reynolds averaged Navier–Stokes equations over the flow depth. Examples are the St. Venant equations, which assume a hydrostatic pressure distribution, or the Boussinesq equations (Woodhead, 2007). The 2D class of models includes full solutions of the two-dimensional St. Venant or shallow water equations and simplified shallow water models where certain terms, such as inertia, are omitted from the controlling equations. Models of this class are MATO (Posada, Silva, Simmonds, & Pedrozo, 2007, pp. 205–241), TUFLOW, Mike 21, TELEMAC, LISFLOOD-FP, and Delf-FLS (e.g., Neelz & Pender, 2009). The computational time is from hours to days. One of the first numerical models developed for wave overtopping-induced erosion of the inner slope of grassed sea-dikes is the BREaching of Inhomogeneous sea Dikes (BREID), developed by Tuan and Oumeraci (2010). On the other hand, 2D models are commonly applied to a broad variety of problems including urban inundation. Simpler 1D methods (Wadey, 2013) such as Mike 11, HEC-RAS, and Infoworks RS (ISIS) (Neelz & Pender, 2009), with computation time in the order of minutes to hours, represent the flooding process under the assumption that the floodplain flow is equal to the channel flow.

Where a broad-scale assessment of extents and depths of flooding is required, GIS-based flood inundation or flood-spreading models (Brown, 2006; Poulter & Halpin, 2008) can be a cost-effective solution. These models do not solve hydraulic equations but perform flood mapping through the spreading of water levels or volumes across a Digital Elevation Model (DEM) by using several techniques (Chen, Hill, & Urbano, 2009; Gouldby, Sayers, Mulet-Marti, Hassan, & Benwell, 2008; Wang, Wan, & Palmer, 2010; Zerger, Smith, Hunter, & Jones, 2002). The computational time ranges from seconds to a few minutes, depending on modifications introduced in the algorithms; therefore these approaches can be easily implemented in Decision Support Systems (see Section 6.6). However, to provide the user with sufficient accuracy they require high-resolution topographic data and are less suited to application in flat areas.

Complementary methodologies to simulate extreme long-term flooding water-level scenarios, based on the application of combinations of different types of hydrodynamic models and probabilistic distributions of the atmospheric and river discharges forcing, are presented in Chapter 7.

2.9 Handling Uncertainty

Uncertainty permeates the whole process of risk assessment and is often ignored. There are two main causes: (1) lack of knowledge either about relevant data or about whether a particular effect will occur; and (2) as a result of the random nature of the events, which itself depends on natural circumstances and their timespan. These random events can include:

1. Errors in the probabilities of flood events: e.g., through the extrapolation of short time series to flood discharges.
2. Inundation area and depth: imprecision due to generalized digital terrain models or because of difficulties in estimating failure probabilities of flood defenses.
3. Type and location of elements at risk: inaccuracies because of generalizations in spatial resolution and categorization of land use data.
4. Value of elements at risk: values are often approximations or have to be disaggregated or have to cope with nonmarketable elements such as valuable habitats.
5. Susceptibility of elements at risk: damage functions are often derived from poor empirical data.

Hazard forecasting and risk assessment systems traditionally concentrated on separately modeling single phenomenon such as sea level, rainfall, waves, river discharges, flash flooding, etc. Each forecasting system comprises a linear flow of data and a combination of different models; for instance: starting with a meteorological model, which provides forcing to a shallow water flow model for forecasting tides and surges; a wave model for forecasting waves nearshore and further models to predict subsequent overtopping and/or flooding; and river flow models for forecasting pluvial and fluvial flooding. The weaknesses (or limitations) of these flood modeling systems include:

- Lack of inter-operability between model components;
- A tendency to consider only a single source of hazard;
- Lack of ensemble or data-assimilation techniques;
- Absence of tracking of estimation errors for uncertainty analysis;
- The need to constrain uncertainties and narrow prediction bounds with model refinement;
- Assessment of the potential associated risk is often limited or even absent with respect to vulnerability and resilience;
- Assumption of historic/static data on the condition of geomorphic landforms and defenses.

Cascading forecast uncertainty in coupled models is an important step to improve the quality of hydrological forecasts (Cloke & Pappenberger, 2009). However, the best methodology to quantify the total predictive uncertainty in hydrology is still debated (Beven, Smith, & Freer, 2008). Sources of uncertainty in the hydrometeorological forecast chain are numerous and include the meteorological forcing, corrections, and downscaling procedure of the meteorological predictions; antecedent conditions of the system (meteorological and hydrological) observation networks; methods of data assimilation (discharge, soil moisture); geometry of the system (including flood defense structures); possibility of infrastructure failure (dykes or backing-up of drains); characteristics of the system (in the form of model parameters); and limitations of the hydrological model to fully represent processes (for example, surface and subsurface flow processes in the flood generation and routing). The importance of the individual components varies in time, depending on the dominant flow regime, and in space, as each catchment is unique (Beven, 2000). It also depends on the interactions between the space-time scales of the predicted event, the main catchment characteristics (area and response time), and the resolution of the meteorological forcing data (Thirel, Rousset-Regimbeau, Martin, & Habets, 2008). A full uncertainty analysis can track all sources of uncertainty and estimate both their relative importance in the system and the total uncertainty from the combination of each component (Pappenberger et al., 2005). The total magnitude of the uncertainty influences the quality of the predictions, the interpretation of model output forecasts, and ultimately its use in decision-making (Ramos, Mathevet, Thielenc, & Pappenberger, 2010).

Many of the issues of projecting future change are addressed by presenting risk as a range of values rather than a single number. This provides an envelope within which the actual future is expected to occur. There are two main approaches: the use of scenarios and probabilistic approaches.

The use of scenarios in risk assessments recognizes that the future is unknowable. For example, knowledge about future socioeconomic developments is limited. In turn, this leads to uncertainties in future greenhouse gas emissions. Further, when subjected to the same emission scenario, different climate models will show different responses, reflecting both imperfect knowledge of the underlying physical mechanisms and internal (natural) climate variability.

A number of different scenarios should be used that sample the underlying assumptions that appear plausible. Commonly an ensemble of climate change simulations obtained from different models and scenarios is used. Scenarios cannot be associated with a likelihood of occurrence and represent ‘‘plausible futures’’ rather than probable outcomes (Von Storch & Zwiers 2013). Hence, scenarios generally address questions of the type “What may happen if _ ?”. The benefit of using scenarios is that decision-makers consider a range of views of what may unfold and understand broad sensitivities of the flood system. Hence, they can develop suitable policies/management. A focus is on options that are robust to the range of existing uncertainty and flexible; that is, they may be adopted in the course of time when expected changes manifest and uncertainty becomes smaller, raising the approach of defining and selecting adaptive pathways (Ranger, Reeder, & Lowe, 2013; Tarrant & Sawyers, 2012). Hence, there can be benefits in considering scenarios that have a low chance of occurring (Randall & Ertel, 2005), to test for the long-term robustness and feasibility of different adaptation approaches over time and the range of scenarios.

In the context of historical changes and present conditions, probabilistic or statistical approaches can be used. For example, the definition of return periods and their uncertainties has become more common with the increase in data availability and computing power. However, this still depends on the availability of data. Extreme events pose a particular set of challenges for implementing probabilistic approaches, because their relative infrequency makes it difficult to obtain adequate data for estimating the probabilities, and this gets worse as return periods increase (Milly, Wetherald, Dunne, & Delworth, 2002).

Communication of the uncertainty within a flood assessment is good scientific practice, maximizing credibility and minimizing misinterpretation, bias, and different interpretations (Kloprogge, van der Sluijs, & Wardekker, 2007). Ineffective communication of scientific research to decision-makers and the public has often proved a barrier to uptake of knowledge by stakeholders. Uncertainty information concerning probabilities is particularly prone to biases, as the concepts themselves are not easy to understand; risk experts separate the probability and magnitude components of a risk, but for nonscientific audiences the perception of risk is often directly linked to consequences and specifically to consequence experienced by the users involved in the assessment. This can lead to an under-appreciation of low-probability, high-impact events (Kloprogge, van der Sluijs, & Wardekker, 2007).

2.10 Capturing Future Changes

Timing and time-scales are important cross-cutting themes that need more attention when dealing with the identification and management of extreme climate and weather events, disasters, and adaptation strategies. The first key issue when dealing with timing and time-scales is the fact that different hazards and their recurrence intervals might fundamentally change with time. This implies that the identification and assessment of risk, exposure, and vulnerability also needs to address multiple time-scales. At present, most of the climate change scenarios focus on climatic change up to the year 2100, while projections of vulnerability often just use present socioeconomic data. However, a key challenge for enhancing knowledge of exposure and vulnerability as key determinants of risk requires improved data and methods to project and identify directions and different development pathways in demographic, socioeconomic, and political trends that can illustrate potential increases or decreases in vulnerability with the same time horizon as the changes in the climate system related to physical-biogeochemical projections (Birkmann, Garschagen, Kraas, & Quang, 2010). This is challenging, as future socioeconomic conditions are more uncertain than biophysical conditions, and for example, a maximum of time frames of 25–30 years is normal in government. Furthermore, the time dependency of risk analysis, particularly if the analysis is conducted at a specific point in time, has been shown to be critical (e.g., Setiadi, 2011). These types of issues should also be considered, but the details of how and to what degree will vary from study to study.

2.10.1 Use of Drivers and Scenario Analysis

As the SPRC model describes the flood system at a single moment in time, the conceptual system needs to sit within a wider analytical framework that allows for time and external and internal changes as a result of different Drivers. Including Drivers is essential when looking at the evolution of the flood system (and flood risk) over time, and requires clarity early in the flood risk assessment (Millner, 2012). This effectively addresses the uncertainties faced when looking at future situations and can range from uncertainties inherent in the modeling process (including scientific understanding of the system) to the range of possible socioeconomic futures and projections of climate change that can affect flooding. Participatory approaches including stakeholder engagement are good practice, maximizing credibility and minimizing misinterpretation, bias, and differences by readers and users (Kloprogge, van der Sluijs, & Wardekker, 2007).

Many of the challenges of communicating possible change are addressed by presenting risk as a range of values rather than a single number. Scenarios (storylines) are often used to illustrate different plausible relationships between cause and outcome, illustrating how current and alternative development paths might affect the future (Moss et al., 2010; Nakićenović et al., 2000; Nicholls et al., 2012a). Hence, scenarios can have multiple dimensions depending on the question being posed. In addition to considering the Drivers in isolation, one approach is to use a range of scenarios which vary the underlying assumptions: at the minimum, estimations can reflect where everything works to expectationsda best-case scenariodand where nothing doesda worst-case scenario; the difference between the best-case and worst-case values can then be used as a measure of the range of risk. There can also be benefits to considering scenarios that have a low probability of occurring (Nicholls et al., 2014; Randall & Ertel, 2005).

How individual parameters within the scenario are represented also needs to be decided (see Table 2.6). For the quantitative components of the system, such as water levels and number of people, future projections commonly draw on global or national level data and are downscaled using statistical methods. For example, with the increase in data availability and computing power, methods such as standard deviation and probabilities have become more common, particularly for the translation of climate model outputs for detailed flood modeling. For some parameters, however, the use of such data to represent local changes could raise the question of plausibility, as a different pattern of change could be experienced: for example, a city may increase in population despite regional or country projections of population decline.

TABLE 2.6 Examples of Representative Scenarios and Data for the Different Aspects of the Flood System

Data Type	Data Source	Social Aspects	Ecological Aspects	Hydrological Aspects
Qualitative	Global	SRES or SSP scenarios		SRES or RCP scenarios
(Semi) qualitative		Human typologies	Vulnerability/resilience assessment (expert opinion)	
Quantitative	Global - national	Downscaled existing population and GDP projections	Designated areas	Water levels and discharge modeled from global climate models (long-term)
	Local	Local data on population and GDP, census data, land-use maps, habitat maps, development plans, buildings database	Changes in specific indicator parameters (e.g., species diversity, salinity, area)	Projections based on 30þ years of historical datadcan be short-term only (10 years)

For the more qualitative aspects of the flood system, such as public perception and human behavior, deciding how (or even whether) to incorporate them is a challenge for assessments largely based on quantitative flood modeling. This represents a key research challenge.

2.10.2 Climate Change

Linking changes in coastal flooding and erosion risk with climate change requires the combination of data, numerical and statistical models, and empirical approaches. For coastal flooding, analyses of wind, wave, tide, surge conditions, and changes in mean sea level are required. In some cases, contributions from river floods need to be considered. It is often found that mean sea level changes appears to be the most relevant climatic factor contributing to observed and potential future changes in extreme sea levels, while changes in other components (such as the wave or storm surge climate) are small and/or highly uncertain (Weisse, von Storch, Niemeyer, & Knaack, 2012). Determining future scenarios of change can be demanding, so it is important to use methods appropriate to available resources (e.g., Nicholls et al., 2014).

2.10.2.1 Mean Sea Level

Over the twentieth century global mean sea level increased on average 1–2 mm/year (Bindoff et al., 2007; Church et al., 2013; Jevrejeva, Moore, Grinsted, & Woodworth, 2008). For the satellite era from 1993 onwards, somewhat higher estimates of about 3 mm/year are provided that are broadly consistent with that derived from tide-gauge data only (Church et al., 2008; Church et al., 2013). For the future, a further increase in global mean sea level is expected primarily as a result of two processes: ocean thermal expansion in consequence of rising temperatures and freshwater input as a result of melting glaciers and ice sheets. Contributions from melting ice sheets are thought to be minor for the twentieth century, but are potentially the largest contributors in the future (Church et al., 2008; Church et al., 2013).

Regional changes in mean sea level can deviate substantially from the global mean. Regional factors therefore need to be considered. Ideally such assessments are based on global projections taking into account regional effects such as vertical land movement or effects from changing ocean circulation (e.g., Katsman et al. 2008, Katsman et al., 2011; Lowe et al., 2009; Slangen, Katsman, van de Wal, Vermeersen, & Riva, 2012). If such regional projections are unavailable, a pragmatic two-way approach can be adopted: extrapolation of observed regional decadal trends for short and medium time scales may be used as long as the decadal variability in the observed records is larger than the changes projected by the IPCC (e.g., Weisse et al., 2014).

For the long time scales (2080s), global projections based on IPCC scenarios may be used if no other regional information is available.

2.10.2.2 Wind Fields

Surges and waves and their long-term changes are intimately connected with statistics of storms, changes in wind speed, direction, and/or frequency. Wave run-up and setup are relevant processes to consider that may influence coastal flooding. Future changes in extreme wave climate depend on corresponding changes in the atmospheric wind fields that are highly uncertain (Christensen et al., 2007). An ensemble approach taking a number of different climate change scenarios and projections from different models into account is therefore applicable for both surges and wave climate. In this way, a range of possible future developments is obtained, allowing for a better quantification of uncertainties. To do so, a simple descriptive approach rather that formal significance tests is proposed for characterizing the information in an ensemble of scenarios (Von Storch & Zwiers, 2013). It should be noted that the statistics of present winds, surges, and waves is quite uncertain, so determining changes will be difficult.

2.10.2.3 Extreme Water Levels

Extreme sea levels may show pronounced fluctuations on seasonal, inter-annual, and decadal time scales. The latter may be associated, e.g., with the nodal cycle (e.g., Méndez, Menéndez, & Losada, 2007; Menéndez et al., 2009). Such fluctuations may be important for any risk assessment related to extreme sea levels. A time-dependent extreme value analysis is therefore proposed to assess the magnitude and phase of such fluctuations. An approach to do so is presented in Méndez, Menendez, & Losada, (2007) and Menéndez et al. 2009. By taking the different time-scales of sea level variability into account, the approach is able to produce short-term forecasts of the probability of exceeding a certain extreme sea level, allowing for the definition of a time-varying flood risk.

2.10.3 Population and Economy Change

For a long-term flood-risk assessment, potential changes in population and asset value should be considered. Specific knowledge may be available at local level and the short term (e.g., development plans), but over longer periods appropriate socioeconomic scenarios need to be created. In particular, population, gross domestic product (GDP), and other scenarios relevant at the scale of the study sites are required. These localized scenarios need to represent coherent, internally consistent, and plausible descriptions of possible trajectories of future conditions based on self-consistent storylines or images of the future. They also need to agree with relevant stakeholders for credibility purposes. The high level of indeterminacy of these factors should be conveyed to local and national stakeholders: these scenarios must be presented as food for thought and action, rather than robust projections of the future.

These social and economic scenario will also need to consider cross-scale interactions (Turner et al., 2003a,b). However, the practical application and analysis of these interacting influences on vulnerability from different spatial scales is a major challenge and in most cases not sufficiently understood. Furthermore, vulnerability analysis, particularly linked to the identification of institutional vulnerability, must consider the various functional scales of climate change, natural hazards, vulnerability, and administrative systems. In most cases, current disaster management instruments and measures of urban or spatial planning as well as water management tools operate on different functional scales compared to climate change. For example, policy setting and management of climate change and of disaster risk reduction are usually the responsibility of different institutions or departments; thus it is a challenge to develop a coherent and integrated strategy (Birkmann & von Teichman, 2010). Consequently, functional and spatial scale mismatches might even be part of institutional vulnerabilities that limit the ability of governance system to adequately respond to hazards and changes induced by climate change. This illustrates the potential complexity of this aspect of flood-risk assessment and the need for clarity on the questions being asked.

2.10.4 Habitat Loss or Change

Coastal habitats can tolerate a degree of flooding by sea water, but are vulnerable to changes in flooding regime, and permanent changes can occur. Including quantitative modeling of the full range of potential impacts on all coastal habitats may not be possible within many coastal flood assessments due to our limited detailed understanding. Hence, an alternative, robust method is needed. Coastal habitats (including seagrass meadows, biogenic reefs, rocky shores, and salt marshes) are generally not affected by individual flood events, but over time, persistent changes in Drivers will have an effect; for example, negative secondary impacts from flooding such as sedimentation over biogenic reefs. Terrestrial habitats (including coastal grasslands, grazing marshes, and sand dunes) can be damaged by seawater flooding. Estuarine transition zones can be regarded as further sources of floodwater particularly when the freshwater level is high. These habitats also act as efficient pathways for transferring floodwaters. As these habitats regularly experience changes in salinity over varying time periods, consequences from one-off flood events are negligible.

However, salinization is likely to produce negative impacts on the species found there; although these habitats will be able to recover, permanent changes to the saline regime potentially though changes in sea level will result in permanent changes to the communities found. These changes can be considered as changes in Pathways for the landward Receptors, but these habitats also represent Receptors in terms of habitat designations, etc.

2.11 Conclusions

This chapter has shown that a holistic approach to coastal flood risk management has significant benefits. Changes in the physical, ecological, and socioeconomic dimensions identified within the SPRC concept all have the potential to change levels of risk. Hence if they can be managed appropriately, this has the potential to regulate levels of risk. By considering these three main aspects of the flood system, a more resilient approach can be adopted that is capable of dealing with flood events better than more traditional approaches (Wardekker, de Jong, Knoop, & van der Sluijs, 2010). Chapters 3, 4, and 5 deal in detail with the different kind of mitigation measures addressing specifically engineering, ecological, and socioeconomic components of the coastal system, respectively. It is important to remember that there are potential interactions between the different classes of techniquesdfor example, beach nourishment (soft engineering) may have ecological consequences, and the effects of ecological management may have influences on the design of artificial structures. In fact, some of these interactions may be planned and intended. The considerations when selecting individual or combinations of techniques are discussed in Chapter 6, while Chapter 7 looks at examples.

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