ENVIRONMENTAL SCIENCE & POLICY 14 (2011) 1121–1131

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/envsci

The meaning of system robustness for flood risk management

Marjolein J.P. Mens[a,b,*], Frans Klijn[a], Karin M. de Bruijn[a], Eelco van Beek[a,b]

[a] Deltares, Flood Risk Management, Rotterdamseweg 185, 2629 HD, Delft, The Netherlands
[b] Twente University, Water Engineering and Management, P.O. Box 217, 7500 AE, Enschede, The Netherlands

ARTICLE INFO

Published on line 14 September 2011

Keywords:
System robustness
Flood risk
Resilience
Vulnerability
Regime shift

ABSTRACT

This paper explores how the concept of robustness can be defined and made operational for flood risk management. Decision making about taking actions to reduce the flood risk is complicated by uncertainties about the current and future flood probabilities and impacts. Because decision makers are increasingly aware of uncertainties, new decision-making approaches are being explored. Among other concepts, robustness is put forward by decision makers in the Netherlands as a way to deal with uncertainties. However, they cannot specify what makes a system more robust. This paper defines robustness as the ability of a system to remain functioning under disturbances, where the magnitude of the disturbance is variable and uncertain. We present a conceptual framework for analysing system robustness, and we suggest how the robustness of flood risk systems can be quantified. The ideas are tested on the Westerschelde flood risk system in the Netherlands. This case shows that analysing system robustness provides additional insight into the effect of flood risk reduction measures on system behaviour.

1. Introduction

Flood risk management has gained increasing attention throughout Europe over the last decades. Since 1998, floods in Europe have caused about 700 deaths and more than 25 billion Euro economic losses (European Commission, 2010). The severe floods of the Danube and Elbe in 2002, and the floods in Central and Eastern Europe in 2005 encouraged the implementation of the European Directive 2007/60/EC. This directive requires member states to identify the areas at risk of flooding, to prepare flood risk maps, and to develop flood risk management plans (European Parliament, 2007). To arrive at these plans, decision makers need to choose between different measures, for example between strengthening embankments and building flood-proof houses, based on decision making criteria.

In common approaches to select or prioritize flood risk reduction measures, a key decision criterion is the cost-effectiveness of the measure, which is the ratio between implementation and maintenance costs and the expected reduction in flood risk. However, if flood risk is expressed in a single number, it remains unclear how the flood impact varies over a range of possible events. Extreme events may lead to an unacceptably high impact or even a point of no recovery. This means that a disaster is possible, but it is uncertain when this will happen.

Recent policy documents about water management in the Netherlands have introduced the term robustness. They aim for example for robust nature, robust water systems and robust decisions (ARK, 2007; National Water Plan, 2008). These documents show that robustness associates with being insensitive to uncertainties, but they do not specify what makes a system more robust nor to what type of uncertainty. Furthermore, some consider robustness as being equal to resilience, whereas others associate robustness with very strong embankments. Implicitly, different interpretations are

* Corresponding author at: P.O. Box 177, 2600 MH, Delft, The Netherlands. Tel.: +31 088 335 8542; fax: +31 088 3358582.
E-mail address: marjolein.mens@deltares.nl (Marjolein J.P. Mens).
1462-9011/$ – see front matter
doi:10.1016/j.envsci.2011.08.003

being used. Because a clear definition lacks, there is a danger of miscommunication among stakeholders.

This paper explores the concept of robustness for flood risk management. Analysing the robustness of flood risk systems is expected to provide insight into how the flood impacts vary over a range of flood probabilities. The approach thus views flood risk management from a systems perspective. A comparable approach was adopted by De Bruijn (2005), who explored the concept of resilience and studied how lowland river systems react to a range of river discharges. She showed that a systems approach may widen the range of flood risk reduction measures considered, because the dynamics of the system are better understood. The research described in this paper takes her work as a starting point, and specifically looks into thresholds in the system response. Thresholds are for example a drastic change from no response to a large response (e.g., because a dike breaches), or the point at which a system is unable to recover from the response to a disturbance. The latter can be called a regime shift.

This paper first proposes a conceptual framework for analysing system robustness, in particular of flood risk systems. The framework is built up from a set of concepts that describe system behaviour, key characteristics of system behaviour, and a set of indicators to quantify these characteristics. We exemplify the framework for flood risk systems.

2. Framework for analysing system robustness

2.1. *Use of the term robustness*

The term robust originates from the Latin *robustus*, meaning ‘strong’ or ‘hardy’. Nowadays, robust means having strength, being strongly constructed, or performing without failure under a wide range of conditions, according to the Merriam-Webster dictionary. In daily life, robustness is seen as a desirable characteristic, for instance of electricity networks that will keep functioning under high demand. In industry and engineering, a robust design is a product or building that can survive all kinds of external forces without failing or collapsing (robust cars, robust buildings, etc.). Robustness is thus associated with strength and durability.

In the scientific literature, robustness is defined in a variety of ways for different fields. We roughly distinguish between system robustness and decision robustness. System robustness is common in the field of engineering and biology, where it refers to the ability of systems to maintain desired system characteristics when subjected to disturbances (Carlson and Doyle, 2002; Stelling et al., 2004; Jen, 2005). Decision robustness – as a characteristic of policy decisions – is common in policy analysis and economics, and is used as a criterion for making decisions under uncertainty (Rosenhead et al., 1972; Bankes, 1993; Lempert et al., 2003; Ben-Haim, 2006). It represents how sensitive a particular decision is to uncertainties. In other words, a decision or policy is considered robust when it performs well under a range of conditions. Although decision robustness may be very useful in the field of flood risk management (Hall and Solomatine, 2008; Merz et al., 2010), this paper focuses on system robustness. To the knowledge of the authors, system robustness has not been made operational for flood risk systems before. Before further defining system robustness, a definition of flood risk systems is required.

2.2. *Flood risk systems*

Flood risk systems are geographical areas along the coast or along a river that have the potential to be flooded. The system comprises biophysical, economic, and social components. The biophysical subsystem includes the soil, water, air, flora and fauna, as well as the elevation of the flood-prone area, and the physical elements to control the flood risk (e.g., embankments and structures). The socio-economic subsystem includes the economic value of land uses, the financial situation of the area, and economic connections to other areas. It also comprises the people that live in the flood-prone area, among other things characterized by their age, their health, their education and their social networks.

Flood risk systems can be disturbed by storm surges at sea, discharge waves in river catchments, or intensive rainfall potentially leading to flash floods. These disturbances vary naturally in time and normally do not cause significant damage. However, extreme disturbances may cause flooding of the system and cause damage and/or casualties. Besides by flooding, the functioning of a flood risk system (working, well-being, recreation, production, etc.) may also be disturbed by other factors, such as an economic crisis, diseases, and wars. These factors are important to consider, as they may negatively affect the robustness of the system to flooding.

2.3. *Defining system robustness*

System robustness is defined as a system’s ability to remain functioning under disturbances. This implies that information is needed on how the system responds to different degrees of disturbance. Therefore, we refer to three streams of literature that address system behaviour in response to disturbances:

(1) Literature on resilience and resistance of flood risk systems (De Bruijn, 2004a,b; Klijn et al., 2004), which defines resistance as the ability to withstand disturbances, and resilience as the ability to recover from the response to a disturbance.
(2) Vulnerability literature (Dow, 1992; Turner et al., 2003; Adger, 2006; Marchand, 2009). Robustness can be thought of as the flip-side of vulnerability (Gallopin, 2006), referring to all characteristics of a system that have the potential to be harmed (Dow, 1992).
(3) Literature on ecological resilience (Holling, 1973; Walker and Salt, 2006), which defines ecological resilience as the ability to absorb disturbances without shifting into a different regime.

All of this literature examines how and why a system responds to disturbances, but all from different ‘perspectives’. How these perspectives are linked is visualized in a theoretic response curve (Fig. 1), which shows the system response as a function of disturbance magnitude (e.g., the river discharge). Some find that a disturbance can also be a gradual change, for

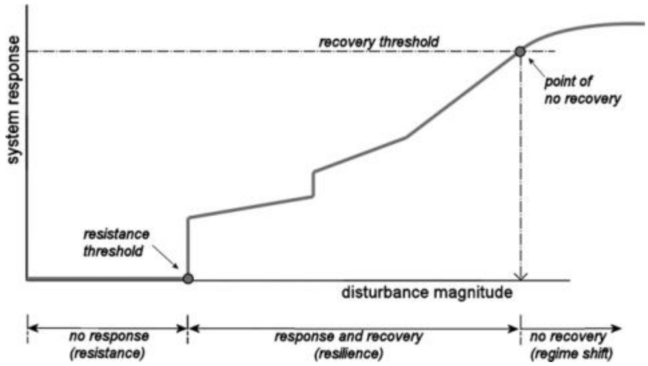

Fig. 1 – Theoretic response curve, showing system response as a function of disturbance magnitude, indicating resistance, resilience, the point of regime shift, and the recovery threshold.

example sea level rise, to which a system could adapt (Carpenter et al., 2001; Wardekker et al., 2010). We, however, consider a disturbance a temporary event. The response refers to a change in system state, for example the flood impact. For small disturbance magnitudes, the system may not respond at all, because it has some degree of resistance. For higher disturbances, the system may respond and recover, because it has resilience (De Bruijn, 2004a,b). Resilience is defined as the ability to respond and recover, which stays closest to the Latin origin *resilire*: to jump back. System robustness is a function of response and recovery.

As mentioned above, vulnerability can be considered the flip-side of system robustness, since it refers to the impact of a disturbing event ('response') and the ability of individuals or society to recover from the impact ('recovery'). Differences with system robustness may arise when vulnerability is analysed for only one degree of disturbance. For example in flood risk management, flood vulnerability maps usually refer to the potential damage due to a 1 in 100 years river discharge. If vulnerability is also analysed for the whole range of disturbances, both the frequent and the rare ones, it can be considered the flip-side of system robustness.

The third perspective on robustness originates from ecological resilience literature, which studies the ability of systems to absorb disturbances without shifting into a different regime. This implies that the response to a disturbance may be too large to recover from. In ecology, this is called a regime shift (Scheffer et al., 2001; Scheffer and Carpenter, 2003), for example the change from a clear-water lake to an algae-dominated lake. Other examples of regime shifts can be found in the regime shift database of the Resilience Alliance (Walker and Meyers, 2004). Studying regime shifts is considered important for the management of systems, because if it is understood under which conditions a regime shift may occur, and what processes drive it, a system can be managed to persist in the desirable regime (Walker and Salt, 2006). A regime shift is indicated in Fig. 1 as the point where the curve intersects the maximum system response from which recovery is possible (i.e., the recovery threshold, indicated in the figure with the horizontal dash-dot line). After a regime shift, the given response curve is not valid anymore.

Thus to understand system robustness, insight is needed into the response curve and the recovery threshold. The curve represents aspects of system robustness, since it visualizes how the system responds to different degrees of disturbance. Because of the system's resistance, the response is zero for a first range of disturbance magnitudes. Because of the system's resilience, it is able to recover from the response to a second range of disturbance magnitudes. If the curve crosses the recovery threshold, the point of regime shift is reached.

To arrive at quantifiable indicators of system robustness, the response curve is described by the following characteristics (adapted from De Bruijn, 2004b):

- Resistance threshold;
- The severity of the response, or amplitude;
- The proportionality of the response, or graduality;
- The point of regime shift.

The resistance threshold is the point where the response becomes greater than zero. For flood risk systems, this point equals the flood protection level. The severity of the response refers to how far the system has moved away from its normal situation. The proportionality is introduced to represent the suddenness of disturbances. It is generally believed that a more proportional response curve is preferable, in contrast to one where the response suddenly shows a large increase with only a small increase in disturbance magnitude (see De Bruijn, 2005). In practice, a more gradual curve implies that floods occur more frequently and therefore people are expected to be better prepared. A high resistance threshold usually co-occurs with a low proportionality, because well-protected areas attract socio-economic developments. The flood probability may then be very small, but that one extreme flood will have a very large impact. A robust system is one where the response curve stays far from the recovery threshold for a large range of disturbance magnitudes.

Quantification of the four characteristics together provides an indication of the system robustness. Fig. 2 visualizes the steps to be taken when analysing system robustness. Step 1 aims to specify *of what* system and *to what* type of disturbance the robustness is analysed (see also Carpenter et al., 2001). Section 2.2 already gave a definition of a flood risk system and the possible types of disturbance. Next, steps 2–4 are explained for flood risk systems.

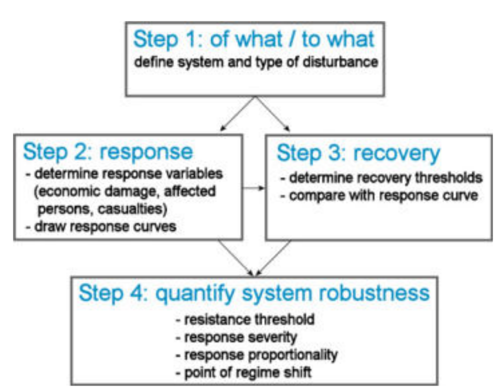

Fig. 2 – Conceptual framework for analysing system robustness.

2.4. Response curves of flood risk systems

For flood risk systems, the response curve shows to what extent the socio-economic system is impacted by the disturbance, through inundation of the flood-prone area. Response variables should be chosen to represent the impact of flooding, for example the economic damage, the number of affected persons or the number of casualties. For each response variable a response curve can be constructed. If there are no economic or social impacts of flooding, the system response is considered to be zero. The response depends on the magnitude of the disturbance as well as on the system characteristics. For example, protection measures such as embankments and storm surge barriers prevent that small disturbances result in flooding, and obstacles in the flood-prone area (such as elevated highways and buildings) may limit the flood extent for higher disturbance magnitudes. In natural river valleys, the socio-economic system can be affected more frequently than in polders with high embankments. In contrast, the response of the river valley will increase more proportionally with increasing discharges, since there are no dikes that can breach. It can be expected that at some point the response (e.g., economic damage) has reached a maximum, simply because all buildings, infrastructure and crops are totally destroyed. However, the recovery threshold may be crossed before the maximum system response is reached, which is the case in Fig. 1.

Although flood risk systems are dynamic systems, the response curve seems a static system representation. The purpose of the response curve is to show the effect of flood risk reduction measures along the full range of disturbances, at a given moment in time. It is thus not a static curve, but a snapshot in time. The shape of the response curve may change over time due to autonomous developments, flood events or implemented measures.

2.5. Recovery thresholds of flood risk systems

Recovery of flood risk systems refers to the process of returning to a normal situation after a flood event. Recovery involves pumping water out, cleaning the flooded area, reconstructing houses and other buildings, repairing infrastructure, etc. The long-term impact of a flood event depends on the time it takes to recover, which in turn depends on the recovery capacity. We define recovery capacity as the general socio-economic level of society, referring to system characteristics that influence the ease with which a system recovers. Recovery capacity is a function of social capital – the ability to *organize* repair and reconstruction, and economic capital – the ability to *finance* repair and reconstruction (cf. De Bruijn, 2005; Marchand, 2009). A high recovery capacity implies that only relatively large impacts will push the system over the recovery threshold.

As a flood risk system is subject to continuous development, it will not return to the exact pre-disaster state after a flood event (De Bruijn, 2005). The degree of recovery can be derived from the system state before and after the event, indicated by key system characteristics such as population number, labour force, drinking water availability, and access to food and electricity. We distinguish between four degrees of recovery: recovery, recovery and betterment, partial recovery, and no recovery (see Fig. 3).

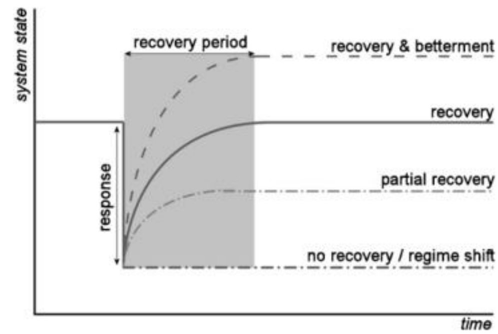

Fig. 3 – System state as a function of time, in response to a flood event, showing four degrees of recovery.

Recovery is when key system characteristics are recovered to 100% of the pre-disaster situation. In many cases, people take the opportunity to improve their houses after the disaster, and policy makers may decide to improve the flood protection. We call this ‘recovery and betterment’. In extreme cases, the system does not recover at all, because the incentive for reconstruction lacks and people do not return; this is called ‘no recovery’, but may also be understood as a regime shift. An example of such a regime shift is found in the Netherlands, where a flooding event in the 15th century lead to a change in land use from agriculture, industry and residential area into nature. De Biesbosch is a national park in the Netherlands and one of the few fresh-water tidal areas in Europe (see Fig. 4b). In the 14th century, De Biesbosch was an urbanized polder, and part of the dike ring area Groote Waard (indicated with a solid line in Fig. 4a). The Groote Waard was reclaimed in the end of the 13th century (Van der Ham, 2003) and consisted of several agricultural polders and large cities such as Dordrecht and Geertruidenberg. In 1421, the St. *Elizabeth flood* flooded almost the entire polder of the Groote Waard. The polder was still recovering from this disaster, when a second storm surge struck in 1424. After the second flood, the community was unable to rebuild the dikes, and they left the polder as an estuary. Later in the 17th century, parts of the estuary were reclaimed again for agriculture. The remaining, unembanked part of the estuary is now a national park: De Biesbosch (Fig. 4b). This regime shift may have been caused by a decreased recovery capacity, for example because the economic resources were already used to rebuild the dikes after the first flood. Another possible explanation is that societal support for reconstruction was lacking, because the two floods happened within only three years. Thus, the system’s ability to recover reduced after the first flood, which made the system unable to recover from the second one.

Partial recovery lies in between no recovery and recovery. For example, New Orleans recovers very slowly from hurricane Katrina and reconstruction is estimated to take 8–11 years (Kates et al., 2006). Currently, society has recovered to 78% of the pre-disaster population and to 87% of the labour force (GNOCDC, 2010). However, it is still unknown whether it will reach 100% recovery in the long term, and it can be

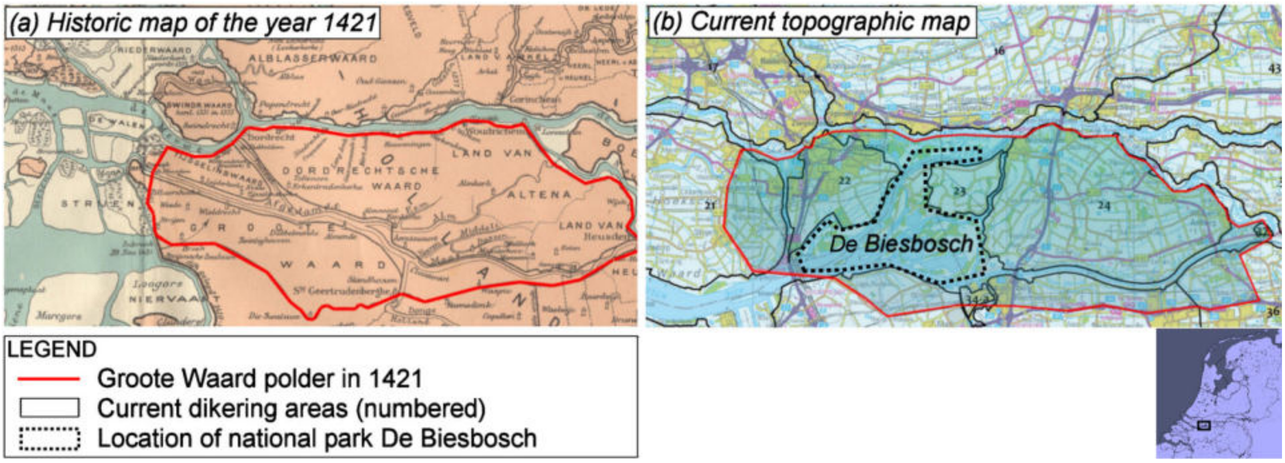

Fig. 4 – (a) Map of Groote Waard and surrounding area in 1421 (adapted from Beekman and Schuiling, 1927); (b) current dike ring areas (numbered), location of national park Biesbosch, and the approximate delineation of the former polder 'Groote Waard'.

questioned whether the system will then be comparable to the pre-disaster situation.

To estimate the potential degree of recovery, we propose to compare the response curve with a recovery threshold. If the response exceeds this threshold, the system is not likely to recover fully. The point of intersection is the point of no recovery. Each response variable has a different recovery threshold.

2.6. *Quantifying system robustness*

To understand system robustness, we suggested studying the system response curve, which can be described by four characteristics. Next, we propose how these characteristics can be quantified.

2.6.1. *Resistance threshold*

The resistance threshold can be quantified by the return period of the highest disturbance magnitude for which the response is zero or negligible.

2.6.2. *Severity of the response*

The severity of the response refers to the impact of the range of disturbance magnitudes. It is difficult to estimate the severity in one number, since it depends on the disturbance magnitudes, and chosen response variable. For flood risk systems, De Bruijn (2004a,b) used the expected annual damage and the expected annual number of casualties to indicate the response severity. This is equal to the flood risk, and can be calculated as the area under the response curve, when the disturbance is expressed in terms of flood probabilities.

2.6.3. *Proportionality of the response*

The proportionality of the response refers to the change in response relative to the change in disturbance magnitude. According to De Bruijn (2004b), discontinuities in the response graph point at the possibility of a disaster. She introduced the measure of graduality. We slightly adapted the original graduality equation. Whereas De Bruijn calculated graduality from the resistance threshold until disturbances with a return period of 1 in 10,000 years, we apply the equation for the whole response curve, from the 1 in 1 year disturbance until the point of no recovery. In this way, it includes the suddenness of the response when the resistance threshold is exceeded, and it has a clear maximum.

Graduality is calculated by dividing the curve into N sections, and expressing the disturbance increase and response increase of each section as fractions of the total range considered (see Eq. (1)). The fractions are then summed and divided by 2 to obtain a value between 0 and 1. A value of 1 indicates that the increase of damage is exactly proportionate to the increase of disturbance. A value close to zero indicates that the total damage increase occurs at once.

$$G = 1 - \frac{1}{2}\cdot\sum_{n=1}^{N}\left|\frac{\Delta D_n}{(D_{\max}-D_{\min})} - \frac{\Delta R_n}{(R_{\max}-R_{\min})}\right| \qquad (1)$$

G = graduality (–)
ΔD_n = change in disturbance for section n ($D_n - D_{n-1}$)
ΔR_n = change in response for section n ($R_n - R_{n-1}$)
$R_{\max}$ = Response at point of no recovery
$D_{\max}$ = Disturbance magnitude that corresponds to $R_{\max}$
$D_{\min}$ = Disturbance magnitude with a return period of one year
$R_{\min}$ = Response that corresponds to $D_{\min}$
N = total number of sections

2.6.4. *Point of no recovery*

To arrive at a measure for the point of no recovery, we need recovery thresholds for each relevant response variable. Little is known about this point, and more likely it is not a distinct point but instead a gradual process or an 'area of no recovery'. Still, studying the response in relation to a potential threshold is expected to provide insight into the scale of a disaster. As a first start, we suggest the following recovery thresholds for four response variables:

(1) Number of casualties > 10% of the region's inhabitants;

(2) Number of displaced people > 30% of the region's inhabitants;
(3) Total economic damage > 50% of the country's Gross Domestic Product (GDP) or a state's Gross State Product (GSP);
(4) Direct economic damage > 100% of the available public financial resources.

If any of these thresholds is exceeded, we assume that recovery will be very difficult and that a regime shift may be induced. Thus, the point of no recovery can be quantified by the return period of the disturbance magnitude at which the response curve intersects with the assumed recovery threshold.

The thresholds are arbitrarily chosen and should be underpinned by empirical research. Also, it can be disputed on what scale the thresholds should be analysed. For example, the number of casualties can be compared to the number of inhabitants in the country or to those in the flood-prone area. This will yield different results. Nevertheless, the point of no recovery is considered to be relevant when comparing the effects of different flood risk reduction measures.

The first threshold is for the number of casualties, and proposed at 10% of the number of inhabitants. If a large percentage of inhabitants deceases, a significant number of houses may not be rebuild. Likewise, if a large percentage of the people are displaced, many of them will potentially not return to the area. The second threshold is thus based on the number of displaced people relative to the number of inhabitants. The more inhabitants are displaced for a longer period, the harder recovery will be. This threshold is chosen at 30%, which comes close to the percentage of displaced people from Zeeland (the Netherlands) during the flood disaster of 1953. As New Orleans shows, infrastructure and essential services (electricity, gas, public transportation, schools, hospitals, and food stores) will not be restored fully as long as people have not returned (Kates et al., 2006).

The third threshold is based on the total economic damage relative to the country's or region's Gross Domestic Product (GDP) (see Arakida, 2006). For example, the economic impact of the 1953 flood disaster in the Netherlands was estimated at 6% of the national GDP (Klijn and De Grave, 2008). It had no significant effect on the long-term economic development of the Netherlands, although the regional societal impact was considered unacceptable. To compare, the economic impact of hurricane Katrina is estimated at 81 Billion US Dollar (Knabb et al., 2006), which is about 44% of the 2005 Gross State Product of Louisiana ($183 billion) (BEA, 2009). Therefore, we suggest considering a critical threshold of 50%.

The fourth threshold that we propose is based on the direct damage relative to the available public financial resources. Mechler et al. (2006) use the term 'financing gap' for the lack of financial resources to restore assets lost due to a natural disaster. They assume that public authorities are obliged to repair housing stock, public infrastructure and relief to the affected population. To estimate the available financial resources, data is needed on tax base, budget deficit, internal and external debt, international loans, aid from other countries or regions, etc. We suggest considering a critical threshold of 100%.

3. Robustness of the Westerschelde flood risk system and alternative configurations

This case study aims to test the robustness analysis framework and to explore the robustness of different system configurations. To be able to calculate the robustness indicators, we require a hydrodynamic model and a damage model. Since we modelled the Westerschelde estuary before (De Bruijn et al., 2008), a range of flooding simulations and the resulting flood depth maps were available. We used the Netherlands' Standard Damage and Casualties model (Kok et al., 2005; Egorova et al., 2008) to estimate the economic damage and number of affected persons. The frequency curve of maximum water levels at Vlissingen was taken from a study by IMDC (2005), and extrapolated to a water level of 6.6 m +MSL, which corresponds to the 1 in 10,000 years water level at Vlissingen in the year 2100 (according to the worst climate change scenario).

3.1. *Step 1: system definition and type of disturbance*

The Westerschelde is a wide estuary in the south-west of the Netherlands connecting the Schelde river to the North Sea (Fig. 5). The flood risk system consists of the Westerschelde estuary and four low-lying polders: Walcheren, Zuid Beveland West, Zuid Beveland Oost and Zeeuws Vlaanderen. We chose the western boundary at the city of Vlissingen. Flooding is assumed to occur from the Westerschelde only, although Walcheren and Zuid Beveland may also be flooded from the North Sea and from the Oosterschelde estuary (closed-off from the North Sea by a storm surge barrier).

The disturbance of interest is a storm surge on the North Sea. This influences the water level at Vlissingen, which naturally varies in time due to tidal patterns. A series of embankments and dunes protects the low-lying polders from flooding. These are designed to withstand water levels that occur once in 4000 years on average. At even more extreme water levels, embankments are expected to fail. Flooding will cause casualties, damage to buildings and infrastructure, as well as income losses due to damaged crops. Some damage occurs indirectly, for example loss of income for the recreation sector and for companies outside the flooded area due to flooded road networks.

In addition to the current system configuration, we are interested in the robustness of three alternative system configurations. Theoretically, three types of measures can be identified: those that increase the resistance threshold by reducing the flood probability; those that decrease the response or reduce the consequences; and those that increase the recovery threshold. From the study of De Bruijn et al. (2008), analysis results of the following measures were available:

- Strengthening dikes (probability reduction): Flood protection levels are differentiated between subareas, based on the expected flood impact. Areas that have a relatively high economic value are protected up to a water level of 6 m +MSL at Vlissingen. This implies raising the dikes with 0.4 m. Other subareas remain protected as in the current configu-

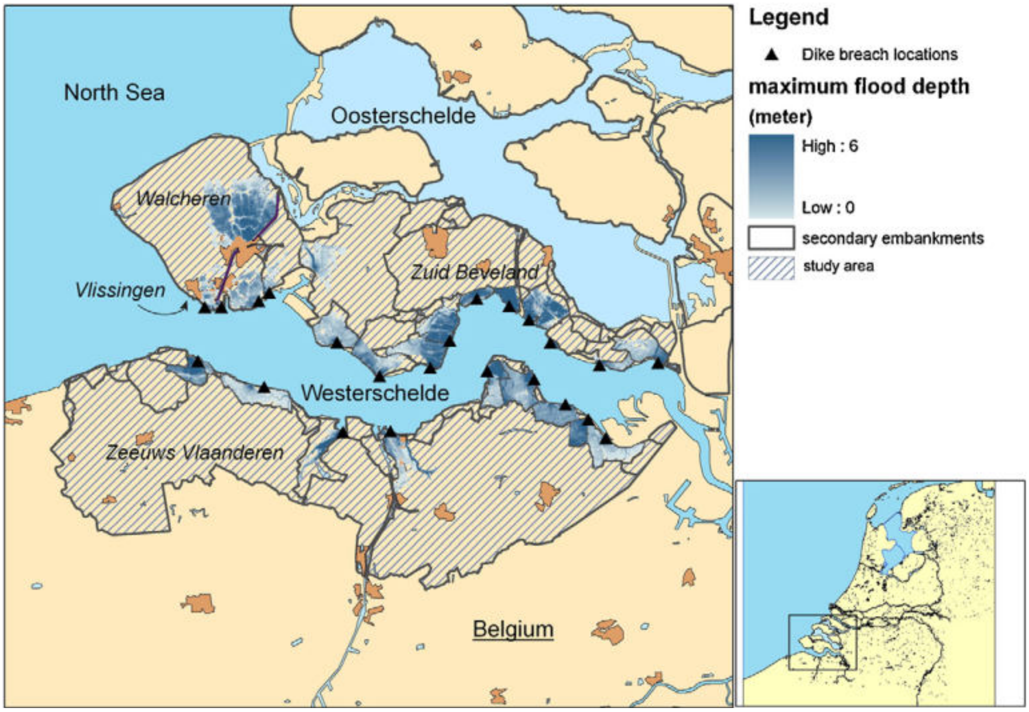

Fig. 5 – Study area with an indication of the flood extent and flood depths.

ration, thus up to a water level of 5.1 m +MSL. Consequently, fewer dikes will breach at disturbance levels of 5.1–6 m +MSL.
- Spatial planning (consequence reduction): For example, building is restricted in areas where inundation depths are expected to be large, or flood-proof building is enforced. It is assumed that spatial planning measures will reduce the economic damage by 30%.
- Storm surge barrier (probability reduction): we assume that a storm surge barrier is built at Vlissingen. This barrier is designed to withstand water levels up to 6.2 m +MSL.

3.2. *Step 2: response*

Fig. 6a shows the estimated economic damage (in million Euros) as a function of the water level at Vlissingen, for the current configuration and the three alternative system configurations. It shows that the economic damage increases with an increasing water level at Vlissingen. When more water is available, this leads to larger water depths and a larger flood extent. Fig. 6b shows the response curve of the estimated number of affected persons.

In the 'strengthening dikes' configuration, no flooding occurs until a disturbance of 5.1 m +MSL. When this resistance is exceeded, only the subareas with a relatively lower economic value are flooded. At a disturbance level of 6 m, the better protected areas will be flooded as well. Compared to the current configuration, 'strengthening dikes' has the same resistance threshold, but a smaller response for disturbances between 5.1 and 6 m.

In the 'spatial planning' configuration, the economic damage is lower for all disturbances greater than 5.1 m +MSL. Thus, the resistance threshold is comparable to that of the current situation. Because spatial planning in this case only implied flood-proof building and not that people are motivated to move to less risky places, it only affects the economic damage and not the number of affected persons.

In the 'storm surge barrier' configuration, the resistance threshold is increased to 1 in more than 100,000 years (i.e., a water level of 6.2 m). For higher water levels, flooding has the same pattern as in the reference configuration.

3.3. *Step 3: recovery thresholds*

We calculated two of the four proposed recovery thresholds, and compared each with the corresponding response curve. The recovery threshold of the economic damage was proposed at 50% of the GDP. The GDP of the province of Zeeland was 8418 million Euros in the year 2000 (CBS, 2010). The threshold of 50% (4209 million Euros) is reached at a water level of about 6.3 m in all configurations except spatial planning. Spatial planning does not reach the threshold at water levels below 6.6 m.

The recovery threshold of the number of affected persons was proposed at 30% of the number of inhabitants in the province of Zeeland (year 2000), equalling 112,000 affected persons. This threshold is indicated in Fig. 6b by the horizontal dashed line. The reference curve intersects the threshold at a water level of 6.0 m. 'Strengthening dikes' and 'spatial planning' do not influence the point of no recovery. 'Storm surge barrier' moves this point to a water level of 6.2 m +MSL.

From the two quantified thresholds, the recovery threshold of affected persons can be considered indicative for the point of no recovery. This point of no recovery is used as the maximum water level for calculating the graduality, for both the economic damage curve and the affected persons curve.

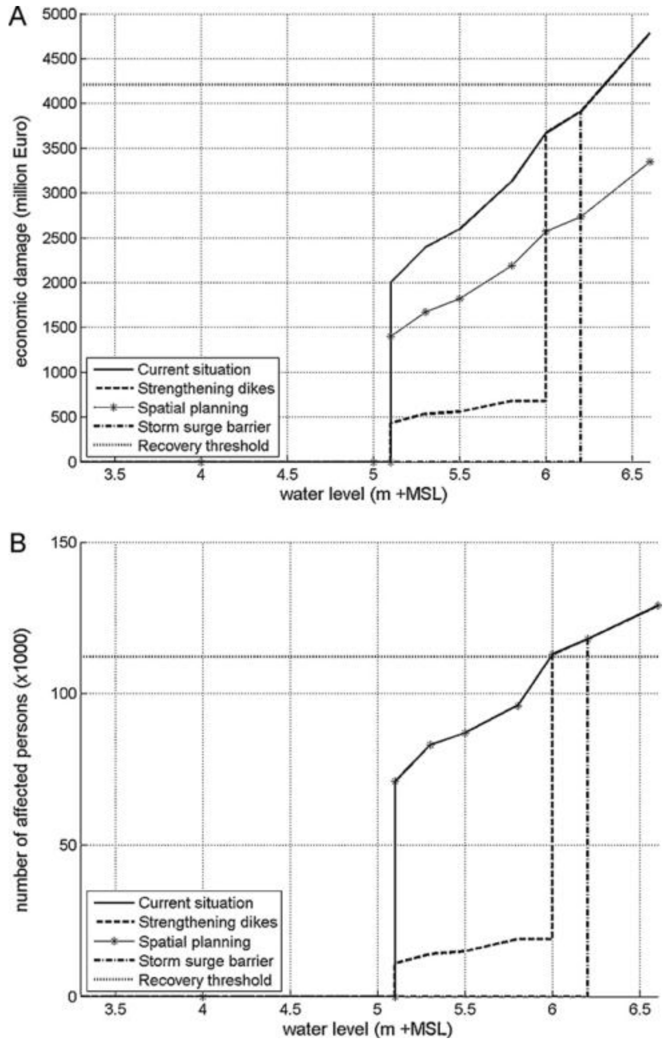

Fig. 6 – Response curves for the current and alternative system configurations, including the recovery threshold: (a) economic damage, (b) number of affected persons.

3.4. *Step 4: quantifying system robustness*

The system robustness indicators were calculated following the methods in Section 2, for both the economic damage and the affected persons. The severity of the economic damage is indicated by the expected annual damage (EAD), and the severity of the number of affected persons is indicated by the expected number of affected persons (ENAP). Results are listed in Tables 1 and 2.

As becomes clear from the two tables, all alternative system configurations show a smaller EAD than the reference, where 'storm surge barrier' shows the largest decrease. Spatial planning reduces the EAD, but not the ENAP, because flood-proof buildings do not affect the number of inhabitants. If a decision would be based only on a reduction in the EAD and the ENAP, the storm surge barrier would be the preferred option. However, the storm surge barrier will probably be the most costly alternative.

Table 1 – Robustness of the four system configurations, based on the economic damage curve: cur = current situation, sd = strengthening dikes, spp = spatial planning, ssb = storm surge barrier.

Characteristic	Indicator	cur	sd	spp	ssb
Resistance threshold	Lowest return period with zero response (1/year)	1/4000	1/4000	1/4000	<1/100,000
Response severity	EAD (million Euro/year)	0.60	0.15	0.42	0.01
Response proportionality	Graduality (–)	0.32	0.07	0.32	0.00
Point of no recovery	Return period where response equals recovery threshold (*p*/year)	<1/100,000	<1/100,000	<1/100,000	<1/100,000
Point of no recovery	Water level where response equals recovery threshold (m)	6.3	6.3	>6.6	6.3

Table 2 – Robustness of the four system configurations, based on the affected persons curve: cur = current situation, sd = strengthening dikes, spp = spatial planning, ssb = storm surge barrier.

Characteristic	Indicator	cur	sd	spp	ssb
Resistance threshold	Lowest return period with zero response (p/year)	1/4000	1/4000	1/4000	<1/100,000
Response severity	ENAP (persons/year)	20	4.2	20	0.3
Response proportionality	Graduality (–)	0.27	0.07	0.27	0.00
Point of no recovery	Return period where response equals recovery threshold (p/year)	<1/100,000	<1/100,000	<1/100,000	<1/100,000
Point of no recovery	Water level where response equals recovery threshold (m)	6.0	6.0	6.0	6.2

The resistance threshold is only increased by the storm surge barrier. The graduality shows the same pattern for the affected persons curve and the economic damage curve. The graduality is reduced when dikes are strengthened and when a storm surge barrier is built. This is because the degree of sudden increase in response is increased. The graduality of 'spatial planning' is equal to that of the reference configuration, although the damage curve shows the smallest absolute 'damage jump'. This is because the graduality is calculated relative to the maximum damage, which is also 30% lower than in the reference. Spatial planning did not influence the affected persons curve, as explained above.

The point of no recovery is only affected by the storm surge barrier, which moves the point from 6.0 m to 6.2 m, in the affected persons curve. The spatial planning configuration moves the point of no recovery in the economic damage curve to above 6.6 m, but we considered the affected persons threshold indicative for the point of no recovery.

3.5. *Case study discussion*

With the Westerschelde application, we demonstrated that it is possible to quantify the response of a flood risk system (in terms of economic damage and affected persons) for different disturbance magnitudes. The response curves of three alternative system configurations were compared with those of the current configuration, and all robustness characteristics were quantified. The response curves are considered a good starting point to discuss system robustness.

From the conceptual framework, we expected that the point of no recovery would be moved further away by implementing consequence-reduction measures, since they would lower the response curve. In the Westerschelde case, the spatial planning indeed moves away this point in the economic damage curve. However, in the affected persons curve, the point of no recovery is only (positively) influenced by the storm surge barrier, a probability-reduction measure. This can be explained by the relatively high number of affected persons that is estimated when the storm surge barrier fails. Although such an event has a very low probability, the proposed recovery threshold will be exceeded immediately. We could say that the storm surge barrier configuration has a very high resistance and no resilience in terms of affected persons. In fact, its resistance threshold coincides with the point of no recovery. However, the economic damage curve is further away from the recovery threshold. This means that if the storm surge barrier would fail, the economic threshold will not necessarily be exceeded; the system has some (economic) resilience.

One of the proposed indicators is the point of no recovery. We assumed that if one of the recovery thresholds is exceeded, this is indicative for the point of no recovery. For example, the number of affected persons exceeds 30% of the inhabitants at a disturbance level of 6.0 m (storm surge level). At that point, the economic recovery threshold is not exceeded yet. As mentioned before, the point of no recovery is more likely an 'area' of no recovery, since recovery is a process and whether an area will finally recover depends on many factors. The proposed recovery thresholds are not a hard distinction between recovery and no recovery. Instead, it shows the scale of a disaster, and it may indicate how likely it is to recover fully. However, it should be further discussed how to use the recovery thresholds in relation to the point of no recovery.

4. Discussion

In the introduction, system robustness was distinguished from decision robustness. Because these concepts have been developed in different fields (biology and ecology versus policy analysis and decision theory) their meaning and use is different. Although both concepts refer to the degree of insensitivity to fluctuations or changes in (external) conditions, three key differences can be identified. First, decision robustness typically focuses on the consequences of decisions for the long term, say 50–100 years ahead, whereas system robustness is analysed for one particular state: a snapshot in time. Secondly, decision robustness relates to all unknown future developments for which decision makers want the decision to be robust (e.g., climate change, economic development and changing societal values). It therefore considers more than one type of uncertainty. In contrast, system robustness narrows down to one type of uncertainty, i.e., the variability of the most relevant disturbance. Finally, since decision robustness is about making decisions, it necessarily takes into account the implementation costs of the decision options in addition to the benefits. An analysis of system robustness does not require this type of information; it can be confined to the most relevant system response and the most relevant disturbance, while implementation costs play no role.

We believe that both concepts are useful for flood risk management. We consider them to be complementary, since they are relevant at a different moment in the decision-making process. System robustness may help the decision maker to identify strategies and measures, while decision robustness may aid to prioritize between identified measures and in planning their implementation in time. Thus, even for systems that are not robust, taking no measures may be the most robust decision from a cost–benefit perspective. To better understand the benefits of each concept, it is suggested to analyse both decision robustness and system robustness for one case.

5. Conclusion

In this paper, we explored several interpretations related to system robustness, which resulted in a conceptual framework for analysing system robustness. We defined robustness as the ability to remain functioning under a wide range of disturbances, and distinguished two main elements: response and recovery. To analyse robustness, we suggested exploring the system response and recovery over a range of disturbance magnitudes. To describe the response curve, we proposed four characteristics: the resistance threshold, the response severity, the response proportionality and the point of no recovery. These robustness characteristics may potentially be used as decision making criteria, but it is still unclear how they can be combined into a decision making framework.

This paper showed that analysing system robustness provides insight into how different types of risk reduction measures affect the behaviour of the flood risk system (response *and* recovery). The novelty of this paper is that it explicitly compares the response curve with a recovery threshold. It turns out that it highly depends on the recovery threshold whether probability reduction or damage-reduction measures will influence the point of no recovery. So, when aiming for robustness, these thresholds should be investigated. To explore the added value of system robustness for decision making, and the applicability of the robustness indicators, more examples are needed.

It is recommended for a next application to compare the robustness of different system configurations that have an equal flood risk. In this way, the added value of the additional indicators can be better evaluated. Furthermore, the recovery thresholds should be validated by historic examples.

Acknowledgements

The research described in this paper is supported by the Knowledge for Climate programme (the Netherlands), and the Deltares research programme 2010. The Westerschelde case was studied in the context of FLOODsite (European Union, 6th framework programme, GOCE-CT-2004-505420).

REFERENCES

Adger, W.N., 2006. Vulnerability. Global Environmental Change 16 (3), 268–281.
Arakida, M., 2006. Measuring vulnerability: the ADRC perspective for the theoretical basis and principles of indicator development. In: Birkmann, J. (Ed.), Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. United Nations University Press, Tokyo, Japan.
ARK, 2007. Maak ruimte voor klimaat! Nationale adaptatiestrategie, beleidsnotitie (English: Make space for climate, national adaptation strategy). Ministeries van VROM, V&W, LNW en EZ, IPO, VNG en Uni van Waterschappen (in Dutch).
Bankes, S., 1993. Exploratory modeling for policy analysis. Operations Research 41 (May–June (3)).
BEA, 2009. Bureau of Economic Analysis, http://www.bea.gov/regional/gsp/ (accessed at 11.11.10).
Beekman, A.A., Schuiling, R., 1927. School atlas der Geheele Aarde (English: School Atlas of the Entire Earth). Uitgeverij Thieme, Zutphen.
Ben-Haim, Y., 2006. Info-Gap Decision Theory: Decisions Under Severe Uncertainty, 2nd ed. Academic Press, London.
Carpenter, S., Walker, B., Anderies, J.M., Abel, N., 2001. From metaphor to measurement: resilience of what to what. Ecosystems 4, 765–781.
Carlson, J.M., Doyle, J., 2002. Complexity and robustness. Proceedings of the National Academy of Sciences 99, 2538–2545.
CBS, 2010. Netherlands Statistics Bureau, http://statline.cbs.nl/ (accessed at 28.09.10).
De Bruijn, K.M., 2004a. Resilience and flood risk management. Water Policy 6, 53–66.
De Bruijn, K.M., 2004b. Resilience indicators for flood risk management systems of lowland rivers. International Journal of River Basin Management 2 (3), 199–210.
De Bruijn, K.M., 2005. Resilience and flood risk management. A systems approach applied to lowland rivers. Ph.D. thesis. Technical University Delft, Delft, the Netherlands.
De Bruijn, K.M., Klijn, F., McGahey, C., Mens, M.J. P., Wolfert, H., 2008. Long-term strategies for flood risk management. Scenario definition and strategic alternative design. FLOODsite report T14-08-01 (online: www.floodsite.net).
Dow, K., 1992. Exploring differences in our common future(s): the meaning of vulnerability to global environmental change. Geoforum 23 (3), 417–436.
Egorova, R., Van Noortwijk, J.M., Holterman, S., 2008. Uncertainty in flood damage estimation. International Journal of River Basin Management 6 (2), 139–148.
European Commission, 2010. http://ec.europa.eu/environment/water/flood_risk (accessed 10.09.10).
European Parliament, 2007. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32007L0060:EN:NOT (accessed 10.09.10).
Gallopin, C.G., 2006. Linkages between vulnerability, resilience, and adaptive capacity. Global Environmental Change 16, 293–303.
GNOCDC, 2010. News Release: Facts for Features Hurricane Katrina Recovery. http://www.gnocdc.org/Factsforfeatures/HurricaneKatrinaRecovery/index.html (accessed 14.09.10).
Hall, J., Solomatine, D., 2008. A framework for uncertainty analysis in flood risk management decisions. International Journal of River Basin Management 6, 85–98.
Holling, C.S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4, 1–23.
IMDC, 2005. Faserapport 1: Composietrandvoorwaarden Maatschappelijke Kosten Baten Analyse Sigmaplan (English: Combined boundary conditions for the cost benefit analysis of the Sigma plan), Deelopdracht 1. Ministerie van de Vlaamse Gemeenschap, Antwerpen, Belgium (in Flemish).
Jen, E., 2005. Stable or robust? What's the difference?. In: Jen, E. (Ed.), Robust Design: A Repertoire of Biological, Ecological en Engineering Case Studies. Oxford University Press, New York.
Kates, R.W., Colten, C.E., Laska, S., Leatherman, S.P., 2006. Reconstruction of New Orleans after hurricane Katrina: a research perspective. PNAS 103. (40).
Klijn, F., Van Buuren, M., Van Rooij, S.A.M., 2004. Flood-risk management strategies for an uncertain future: living with Rhine river floods in the Netherlands? Ambio 33 (3), 141–147.

Klijn, F., De Grave, P., 2008. Grenzen aan de gevolgen van een overstroming? Discussiestuk voor Waterveiligheid 21e eeuw (English: Limits to the consequences of flooding? Discussion paper for the project Watersafety in the 21st century). Deltares Report Q4348.50, Delft, the Netherlands (in Dutch).
Knabb, R.D., Rhome, J.R., Brown, D.P., 2006. Tropical Cyclone Report Hurricane Katrina 23–30 August 2005. National Hurricane Center.
Kok, M., Huizinga, H.J., Vrouwenvelder, A.C.W.M., van den Braak, W.E.W., 2005. Standaardmethode 2005: Schade en Slachtoffers als gevolg van overstromingen. HKV Lijn in Water, Lelystad, the Netherlands (in Dutch).
Lempert, R., Popper, S.W., Bankes, S.C., 2003. Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis. RAND, Santa Monica.
Marchand, M., 2009. Modelling coastal vulnerability. Design and evaluation of a vulnerability model for tropical storms and floods. Ph.D. thesis. Delft University of Technology, Delft, the Netherlands.
Mechler, R., Hochreiner, S., Linnerooth-Bayer, J., Pflug, G., 2006. Public sector financial vulnerability to disasters: the IIASA CATSIM model. In: Birkmann, J. (Ed.), Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. United Nations University Press, Tokyo, Japan.
Merz, B., Hall, J., Disse, M., Schumann, A., 2010. Fluvial flood risk management in a changing world. Natural Hazards and Earth System Sciences 10, 509–527.
National Water Plan, 2008. National Water Plan. Ministry of Transport, Water Management and Public Works, the Netherlands.
Rosenhead, M.J., Elton, M., Gupta, S.K., 1972. Robustness and optimality as criteria for strategic decisions. Operational Research Quarterly 23 (4), 413–430.
Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B., 2001. Catastrophic shifts in ecosystems. Nature 413, 591–596.
Scheffer, M., Carpenter, S., 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends in Ecology and Evolution 18 (12).
Stelling, J., Sauer, U., Szallasi, Z., Doyle, F.J., Doyle, J., 2004. Robustness of cellular functions. Cell 118, 675–685.
Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. Proceedings of the national academy of science 100, 8074–8079.
Van der Ham, W., 2003. De Grote Waard, geschiedenis van een Hollands landschap (English: Landscape History of the Grote Waard). Uitgeverij 010, Rotterdam. ISBN: 90 6450 506 3.
Walker, B., Meyers, J.A., 2004. Thresholds in ecological and social–ecological systems: a developing database. Ecology and Society 9 (2), 3., In: http://www.ecologyandsociety.org/vol9/iss2/art3.
Walker, B., Salt, D., 2006. Resilience Thinking Sustaining Ecosystems and People in a Changing World. Island Press, Washington, DC.
Wardekker, J.A., De Jong, A., Knoop, J.M., Van der Sluijs, J.P., 2010. Operationalising a resilience approach to adapting an urban delta to uncertain climate changes. Technological Forecasting and Social Change 77 (6), 987–998.

Marjolein Mens is a researcher in the field of flood risk analysis and management, and has been working at Deltares (The Netherlands) since 2006. She holds a Master's degree in Hydrology and Water Management from Wageningen University (The Netherlands). Currently, she is working on her PhD research focusing on the analysis of robustness of flood and drought risk systems, at both Deltares and Twente University. Her work includes flood hazard assessment, inundation modelling, flood damage assessment and the development of decision-support models.

Dr. Frans Klijn is senior specialist in Delta Technology, working at Deltares (The Netherlands) since 1996. Trained as a physical geographer and landscape ecologist, he has been working on River Basin and Coastal Zone Management since 1980. In the nineties, he played an important role in the societal debate on the management of the Netherlands' large rivers, which culminated in the Room-for-Rivers policy. Presently, he co-ordinates research on climate-proof flood risk management of the Netherlands' Knowledge for Climate Program.

Dr. Karin de Bruijn is senior researcher in Flood Risk Management, working at Deltares (The Netherlands) since 1998. Trained as a hydrologist, she has been working on flood risk analysis and assessment, flood inundation modelling, flood casualty assessment and the development and assessment of long-term flood risk management strategies in an uncertain future. In 2005 she defended her PhD thesis titled 'Resilience and flood risk management, a system's approach applied on lowland rivers'.

Prof. Eelco van Beek is professor Integrated Water Resources Management at the University of Twente (The Netherlands), as well as Water Resources specialist at Deltares (The Netherlands). Over the last 40 years, he has been actively involved in many water resources research projects in the Netherlands and abroad with a focus on drought risk, environmental flow and water allocation. He was leader of WL | Delft Hydraulics' team for the important Policy Analysis for the Water Management for the Netherlands (PAWN). Presently, he co-ordinates research on climate-proof drought risk management of the Netherlands' Knowledge for Climate Program.