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Five principles to enable societies to cope with extreme weather events

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DOI

[10.1016/j.envsci.2017.02.001](https://doi.org/10.1016/j.envsci.2017.02.001)

Publication date

2017

Document Version

Final published version

Published in

Environmental Science & Policy

Citation (APA)

de Bruijn, K., Buurman, J., Mens, M., Dahm, R., & Klijn, F. (2017). Resilience in practice: Five principles to enable societies to cope with extreme weather events. *Environmental Science & Policy*, 70, 21-30. <https://doi.org/10.1016/j.envsci.2017.02.001>

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Resilience in practice: Five principles to enable societies to cope with extreme weather events



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ARTICLE INFO

Article history:

Received 13 August 2016

Received in revised form 1 February 2017

Accepted 1 February 2017

Available online 10 February 2017

Keywords:

Resilience

Resilience principles

Disaster risk management

Extreme weather events

ABSTRACT

The concept of resilience is used by many in different ways: as a scientific concept, as a guiding principle, as inspirational 'buzzword', or as a means to become more sustainable. Next to the academic debate on meaning and notions of resilience, the concept has been widely adopted and interpreted in policy contexts, particularly related to climate change and extreme weather events. In addition to having a positive connotation, resilience may cover aspects that are missed in common disaster risk management approaches. Although the precise definition of resilience may remain subject of discussion, the views on what is important to consider in the management of extreme weather events do not differ significantly. Therefore, this paper identifies the key implications of resilience thinking for the management of extreme weather events and translates these into five practical principles for policy making.

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1. Introduction

Many policy makers and organisations use resilience as a paradigm or inspirational concept. International agreements in three post-2015 agendas – the Sustainable Development Goals, the Sendai Framework for Disaster Risk Reduction, and the Paris Agreement under the United Nations Framework Convention on Climate Change – all call for resilience (Roberts et al., 2015) and many policy documents, such as those from the Asian Development Bank (ADB, 2014), European Union (EU, 2013), Government of the Netherlands (MOIE, 2015) and UK Environment Agency (Dilley, 2016) refer to resilience as something to pursue. Yet, resilience often is more of a buzzword than an operational paradigm (Linkov et al., 2014). At the same time, a large number of more theoretical publications on the meaning of resilience and its relation with concepts such as vulnerability, sustainability, robustness, adaptive capacity and recovery have appeared in the academic literature in the past years (e.g. Davoudi, 2012; Folke, 2006; Pendall et al., 2010; Walker et al., 2004). For policy makers and practitioners it is, however, often not clear how the main notions of resilience thinking translate into practical implementation. Hence, the aim of this paper is making the rather abstract and multi-interpretable resilience concept tangible for policy makers.

The increasing use of the resilience concept in policy documents shows that the concept appeals to policy makers. This is likely not only because resilience has obtained a positive connotation in the policy discourse, but also because it covers significant elements that are missed in approaches to the management of extreme weather event risks that are currently in use (Davoudi, 2012; Linkov et al., 2014; Restemeyer et al., 2015). For instance, disaster risk management approaches, particularly those for extreme weather events, do not explicitly capture the difference between low probability/high consequence events and high probability/low consequence events, nor do they include all consequences, since some are quite difficult to quantify (e.g. indirect damages, reputation loss, costs related to evacuation). Furthermore, risk management approaches that are currently applied often have a sectoral focus and pay limited attention to recovery capacity and recovery rate. At the same time, climate change and changes in society fundamentally challenge conventional risk approaches (Merz et al., 2010a). This is why a wider, more comprehensive approach is needed. The resilience concept may facilitate such an approach.

To support policy makers in meeting their objective of increasing resilience, the academic debate on resilience should be translated into practice. Therefore, we identify the main notions from the scientific resilience debate and translate these into five principles that can be used by policy makers to develop strategies that enhance resilience. We focus on resilience to extreme weather

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events, such as droughts, floods and typhoons, though the five principles could be applied to any disaster risk management problem. The principles will be illustrated with examples and two cases.

2. Resilience

2.1. Defining resilience

Although resilience was already used by physical scientists and ecologists in the 1960s, a paper on the resilience of ecosystems (Holling, 1973) set in motion the development that has become the field of 'resilience science', which studies the linkages between social and natural systems and the dynamics of changes in systems (Davoudi, 2012; Milkoreit et al., 2015). The meaning and use of resilience has changed over time, though as yet it remains an ambiguous concept that is used in different ways by different people (Béné et al., 2014; Davoudi, 2012; Olsson et al., 2015; Restemeyer et al., 2015; Walker et al., 2004).

Holling (1973) introduced resilience in ecology as the capacity of a system to persist within a domain of attraction in the face of disturbances and changes in state variables, driving variables and parameters. He contrasted persistence, which can imply that a system has multiple 'domains of attraction' or equilibria, with stability, which implies one single equilibrium. Later, Holling (1996) distinguished the two related interpretations of resilience as engineering resilience respectively ecological resilience. Engineering resilience focuses on how fast a system returns to a steady-state after a disturbance and how large the disturbance needs to be before a system is pushed out of its steady-state (i.e. the resistance of the system) (Davoudi, 2012; De Bruijn, 2004; Folke, 2006). Maintaining a function and conservation of an existing situation are elements of engineering resilience. Ecological resilience, on the other hand, does not focus on a single steady-state. It is the ability of a system to cope with disturbances, whilst allowing its natural development and change. Although it also looks at the magnitude of a disturbance that can be coped with by a system without change, once it crosses a threshold the system may change structure and reach a different state (Davoudi, 2012). Ecological resilience is about the functioning of the system, rather than about maintaining a steady-state (Adger, 2000) and reflects the much higher degree of complexity of ecological systems as compared to engineering systems. With the application of the concept of resilience to social systems a third type of resilience emerged: socio-ecological or evolutionary resilience. Socio-ecological resilience implies that a system does not necessarily have one or more equilibrium states, but is adapting and changing continuously (Davoudi, 2012). In addition to persistence, socio-ecological resilience explicitly includes adaptability, which is the capacity of actors in a system to adapt to gradual change, and transformability, which is the capacity to create a fundamentally new system (Folke et al., 2010; Walker et al., 2004). It focuses on the interplay between disturbances, reorganization, sustaining and developing and encompasses adaptive capacity, learning and innovation that humans are capable of.

Next to the rather abstract debate on meaning and definition of resilience, the concept has been adopted and interpreted in many policy contexts. In particular in the contexts of climate change and disaster risk management resilience thinking has spread among interdisciplinary scientists and policy makers. In a policy setting resilience is rarely defined with great precision, but rather used as a versatile term of which the meaning can be adapted to the circumstances (Funfgeld and McEvoy 2012; Pendall et al., 2010). Resilience then becomes an umbrella term for a system property that is good and worth pursuing, but can be interpreted by everyone in its own way. Instead of being an objective system

descriptor, resilience becomes a normative concept; a desirable system characteristic (Milkoreit et al., 2015; Olsson et al., 2015). This does not mean that no definitions of resilience are given at all, but rather that they often refer to multiple aspects. For instance, the 100 Resilient Cities Initiative defines urban resilience as "the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience" (www.100resilientcities.org/resilience) and UNISDR (2009 p.24) defines resilience in the context of disaster risk reduction as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions".

In definitions of resilience the threat to which the system should be resilient is often not specified; the focus is on general system characteristics. However, operational definitions are needed when resilience is to be quantified, monitored or addressed by policies (Biggs et al., 2012; De Bruijn 2005; Shaw 2012; Wardekker et al., 2010). In those cases both the system and the relevant disturbance should be clearly specified – "resilience of what to what?" (Carpenter et al., 2001). In addition to enabling the measuring of resilience, those definitions also enable targeting measures to the specific threat and its consequences. For example, if disruptions in power supply limit the resilience of cities, the choice of measures to address this is specific for the kind of threat: for flooding hazards raising power substations could increase resilience, whereas for wind hazards putting cables underground or removing trees next to power lines could be useful. If definitions are used that are not specific regarding the system and disturbance, the focus is usually on generic capabilities which enable societies to cope with damages in some elements, or which facilitate recovery. In the example of power supply this could be to increase redundancy in the network. When resilience is used to analyse human–environment systems two other questions are important: "resilience to what ends?", i.e. what is the purpose or desired outcome of resilience, and "resilience for whom?" (Davoudi, 2012). Increasing resilience is expected to lead to a desirable outcome, but what is desirable in a social context is normative. Similarly, decisions on who should be resilient can involve value judgements about priorities and trade-offs (Berkes and Ross, 2016). For instance, increasing urban flood resilience by measures that affect rural residents need to be negotiated in a political process.

2.2. Main notions of resilience thinking to cope with extreme weather events

Although clear differences exist between definitions of engineering, ecological and socio-ecological resilience, we find that there are also commonalities. Most scientists and policy makers consider resilience as a system property that describes the system's reaction to disturbances and changes and they are concerned with to what degree systems are able to cope with disturbances now and in the future. Although often a return to an equilibrium is mentioned (Davoudi, 2012), i.e. engineering or ecological resilience, the need for adaptation or transition – elements of socio-ecological resilience – are usually also discussed but named differently. There is thus agreement that these elements are also important for the ability to cope with disturbances, not only temporary ones, but also trend-wise changes. Particularly in the area of risk and disaster management for extreme weather events views on what is important to enhance resilience do not differ significantly. This section discusses these main notions of resilience thinking, with a focus on coping with

short-lived extreme weather events. Although more or different notions of resilience thinking can be identified (e.g. Biggs et al., 2012; Restemeyer et al., 2015; Wardekker et al., 2010), we find those mentioned below the most relevant for policy making to cope with extreme weather events.

A first element is that the notion of *systems* is essential to resilience (Olsson et al., 2015). System's thinking lies at the core of resilience thinking as resilience is essentially a characteristic of a system. When addressing the question "resilience of what to what?" the system needs to be defined (De Bruijn 2005; Linkov et al., 2014; Pendall et al., 2010). Systems subject to extreme weather events are, however, extremely complex as variables in many domains interact at multiple scale levels. For instance, consider the subsystems involved in analysing resilience of a river basin to droughts: economic (agricultural production), social (household survival), biophysical (river hydraulics, weather) and engineering (irrigation) systems are just a few examples of the many interacting domains.

The notion of *reaction* to disturbances is the second element that is essential to resilience. A recurrent academic discussion topic on the meaning of resilience is the perceived contradiction between resistance and resilience (Olsson et al., 2015). Resilience in socio-ecological systems implies change as opposed to resistance, which means no change. In flood risk management the resistance-resilience dichotomy is also common (De Bruijn 2004; Douven et al., 2012; Restemeyer et al., 2015). A system that has sufficient resistance to cope with a disturbance shows no response, while extreme events which cannot be resisted cause an adverse reaction and call for resilience in order to recover from that reaction. In flood risk management, resistance is often related to embankments or other structural measures, while more resilient approaches generally also include embankments but only to protect the most vulnerable parts and complemented by non-structural measures in other parts of the system. The degree of disturbance which does not result in a reaction can be understood as the resistance threshold. Above that threshold the system will respond and may recover to its pre-disturbed state, or shift to a new state if the recovery threshold is also exceeded (Mens et al., 2011).

Many theoretical and applied studies analyse how the resilience of systems can be enhanced (e.g. ARUP 2014; Biggs et al., 2012; Crowe et al., 2016; McDaniels et al., 2008). From a systems perspective there are several elements that enhance resilience and help a system to remain functioning in the face of disturbances. Among the principles that Biggs et al. (2012) list, diversity, redundancy and connectivity are important generic resilience-enhancing system properties. A higher diversity provides options and alternative courses of actions during a disturbance. For instance, Aerts et al. (2008) apply the concept of diversification through proposing a portfolio of measures: higher embankments, flood proofing houses and creating compartments (Klijn et al., 2010). Redundancy ensures that elements of a system can compensate for each other if individual elements fail due to the disturbance (Biggs et al., 2012). For instance, a desalination plant with spare capacity can compensate for reduced surface water intake capacity during droughts. Connectivity facilitates the exchange of information and materials, which is necessary for the functioning of systems (Biggs et al., 2012). In disaster response communication, for instance, connectivity among first responders and between first responders and affected population is essential to keep systems functioning. For diversity, redundancy and connectivity there is a trade-off between the level and the functioning of the system. Too much connectivity could lead to the dispersal of a disturbance in the system, too much redundancy comes at a cost, and too much diversity may jeopardise the effectiveness of a system. Yet, although the optimal levels may be

difficult to determine, there is general agreement on the notions of which system properties support its *remaining functioning*.

Another important notion in resilience is *recovery*. Particularly in engineering resilience, the focus is on how fast a system returns to its pre-disturbed state after a disturbance (Holling, 1996). McDaniels et al. (2008) focus on the rapidity of recovery as a key element in resilience and highlight that it can be improved by ex-ante mitigation and ex-post response activities. If power supply is disrupted due to a severe storm it makes a large difference if the disruption is a few hours or a few days. The rapidity of recovery depends on the recovery capacity, which in its turn depends on the elements mentioned above – diversity, redundancy and connectivity – but also on other elements of the system. For instance, in social systems elements such as preparedness and knowledge on possible counteractions can affect recovery, as well as resources. High-income households typically recover faster from a disaster than low-income households due to savings, access to communication channels and insurance, and employment (Masozera et al., 2007).

A final notion that we include in our discussion is that enhancing a system's resilience is by definition forward-looking. And when considering the future, we might as well acknowledge that systems must not only be resilient to current disturbances, but also into the *future*. Therefore, adaptation or transformation may be required to ensure persistence also in the long run (Folke et al., 2010; Walker et al., 2004). Adaptivity can be seen as the capacity of a system or its actors to influence resilience by changing parts of the system, and transformation as the capacity to create fundamentally new systems (Walker et al., 2004). In complex socio-ecological systems adaptation and transformation take place at multiple scales. Dynamic interplay of persistence, adaptations and transformations at different scales contribute to the overall resilience of the larger system (Folke et al., 2010). Yet, transformations at the larger scale may also be required. An example of a change that affects the resilience of delta societies to low flows in rivers is increasing salinity due to sea level rise. This may require large transformations, for instance a shift to other crops or from open-air to greenhouse agriculture with closed water systems, or to abandoning agriculture at some locations. Transformations may be deliberate or forced by crises and disasters, which form windows of opportunities for innovation and change. This is also clear from the disaster management practice, where transitions to completely different policies are often observed after a disaster has happened. Deliberate transformation (and adaptation) follows from the ability of socio-ecological systems to incorporate learning (Biggs et al., 2012; Carpenter et al., 2001), or to timely foresee that change is needed because the current policy is bound to fail in the future (Klijn et al., 2015). Learning, though, is just one element in the broader question on how systems remain resilient over time. Several ideas have emerged in literature so far, such as the idea of 'bouncing forth' (Davoudi, 2012; Manyena et al., 2011) 'bouncing back in better shape' (Wardekker et al., 2010), 'build back better', 'muddle through' and the idea of adaptive cycles (Berkes and Ross, 2016; Pendall et al., 2010). This is still an active field of research with several unresolved research questions.

3. Missing aspects in management of extreme weather events

The management of extreme weather events is often risk-based. Risk is generally understood as the combination of the probability of a hazard and its consequences (Jonkman et al., 2003; UNISDR 2009). The consequences are determined by the exposure of people, property, infrastructure and other elements subject to extreme weather events, and by their vulnerability to the event. The risk of extreme weather events is often expressed in terms of

the (average) expected annual damage or (average) expected annual number of casualties (Jonkman et al., 2003; Kind, 2014). These risks can be evaluated by comparing them with acceptable risk levels or in an economic assessment. Reducing risks requires taking measures that reduce either the probability of an event from happening or its consequences. An economic cost-benefit analysis can provide insight into the efficiency of proposed measures. While the investment costs are relatively easy to determine, the benefits of a measure – the achieved risk reduction – are much harder to establish and usually contain considerable uncertainty (Kenny, 2012; Merz et al., 2010b). Furthermore, not all relevant potential impacts of measures can be expressed well in monetary terms, such as loss of lives and damage to cultural heritage. Other criteria are thus needed.

A risk approach centres on identifying vulnerabilities in a system and proposing measures for elements in the system so that they are able to withstand hazards to an acceptable level (Linkov et al., 2014). This often results in a focus on single elements of the system, such as a specific location or a specific type of infrastructure (this is also typically the scope of a cost-benefit analysis). For a thorough understanding of the potential degree of societal disruption and the rate of recovery it is, however, important to analyse what may happen in one single event instead of at one specific location or element. This means that the interrelations between the sub-systems within the system (physical and societal) and overall system behaviour need to be understood.

If a risk approach is applied using a straightforward cost-benefit analysis, a rare disaster with large consequences is equivalent to frequent disasters with small consequences, as they are equivalent in terms of expected damage. However, the perception of these events is very different (Bubeck et al., 2012; Kahneman and Tversky, 1979; Slovic et al., 1977). As a result, engineering and economic approaches optimising designs and protection standards may diverge from actual preferences and decisions taken by policy makers. At the same time optimising approaches often lose view of the broader context, such as what happens if beyond-design events occur. Moreover, risk approaches and disaster risk management generally focus on the current hazard, exposure and vulnerability. Often, models are employed that use measured, past data and assume stationarity, which is an unrealistic approach in complex, socio-ecological systems (Milly et al., 2008). Future uncertainty, including climatic and societal changes, need to be considered in disaster risk management plans. Such changes may require adaptations in systems, but they may also create opportunities to design a more resilient system with a larger ability to cope with extreme weather events. Thus, adaptive planning could increase the resilience for future generations.

In disaster risk management a shift away from enhancing the recovery rate after a disaster has happened and towards disaster risk reduction can be observed in the past 30 years (UNISDR, 2004). The effort to reduce losses of properties and lives translates into much greater attention for protective strategies and a holistic approach, and with the advance of scientific knowledge, policies can be developed to protect people from disasters caused by extreme weather events (UNISDR, 2004). In addition to attention for risk-based approaches, which consider all potential events rather than responding to the last event, there is also more attention for building back better and innovation if measures are taken in response to a disaster (e.g. Fan, 2013; Lyons, 2009). The lessons from resilience thinking can be used to further complement and improve the risk approach. Building resilience fits better with the increasingly complex, non-linear systems and uncertainty in the current situation and on future developments that are part of our society. The call for resilience in many policy documents may be considered as an expression of the need to take into account

those aspects that are obviously missing in oversimplified risk approaches.

4. The five resilience principles

To enhance the resilience of societies to cope with extreme weather events, we propose five principles which help to consider those aspects that are missing in risk approaches. These principles follow directly from the analysis of the main notions discussed above and are:

1. Adopt a system's approach;
2. Look at beyond-design events;
3. Build and prepare infrastructure according to 'remain functioning' principle;
4. Increase recovery capacity by looking at social and financial capital; and
5. Remain resilient into the future

These five principles are elaborated in the following sections and illustrated with examples from the practice of management of extreme weather events.

4.1. Adopt a system's approach

Understanding of the entire system – including the physical, environmental, social and economic aspects – is required to define effective measures tailored to the society that they should protect and support (De Bruijn et al., 2014). A system's approach means that the system is studied as a whole and that different subsystems, areas and processes within the system are viewed as interlinked. As systems may be massive and complex, simplified models can be developed that can help practice to identify the key elements and linkages using methods and techniques developed in the field of systems thinking (Meadows, 2008; Simonović, 2011). Disaster risk managers need to understand the chain of events from the first indications of an imminent threat due to extreme weather to the recovery of the impacts after the extreme weather event (De Bruijn et al., 2016). As the systems are dynamic, feedback loops and changes over time also require attention. An example is the study of Newell and Wasson (2002), who use a system's approach to understand the development of the interaction between floods, embankments and the society's vulnerability.

The consequences of an extreme weather event are in many cases not only felt in the directly affected area, but also in other areas through linkages in systems. Drought affecting an agricultural area can affect the poor in cities through increasing food prices. A typhoon hitting a power plant may affect electricity supply in a much larger area. The 2011 Thailand floods affected production processes globally through linkages in the supply chains of electronics and automotive industries (Haraguchi and Lall, 2015). A system's approach could be used to identify these potential linkages.

Two examples of applying a system's approach in flood risk management are a method for flood risk analysis in river deltas (De Bruijn et al., 2014) and the development of a mobile warning service for farmers in Bangladesh (Cumiskey et al., 2015). River basin systems are hydrologically connected: what happens upstream can affect downstream areas. This is particularly relevant when assessing flood risks in an embanked delta: a breach upstream will lower water levels, and hence flood risks, downstream. Protecting high-value areas (an urban area) by deliberately flooding low-value areas (agriculture) is a common flood management strategy, for instance used during the Mississippi floods in 2011 (Olson and Morton, 2012). Hence, rather

than looking at flood risk at a single location, flood risk in the whole system needs to be assessed. De Bruijn et al. (2014) did so to assess the probability of flood events with many fatalities and found that the overall flood risk is much lower than previously calculated. The other example of a measure that is based on understanding the whole system is a mobile service (short messaging service or interactive voice response) that provides dedicated local flood forecast to farmers, enabling them to postpone harvesting until just before their land floods. This increases yields and reduces the probability of losing crop and income (Cumiskey et al., 2015), and thus reduces damages. This measure required a thorough understanding of the behaviour of the farmers, their needs, the agricultural system and the river system.

4.2. Look at beyond-design events

The risk perception of events with a small probability but large consequences is often different from the 'objective' risk as calculated in engineering or economic analyses (Burns et al., 2010; Kunreuther, 1980). Most people are supposedly risk-averse and policy making processes can turn the focus on specific hazards with a small probability, but high impact. Rare events with disastrous and lasting consequences may call for protection against higher costs than justified by a standard cost-benefit analysis. For instance, in the Netherlands, societal disruption was recently added as an additional criterion to inform the discussion on flood protection standards next to economic efficiency (Van der Most et al., 2014).

A resilience approach considers the entire possible spectrum of events – below and above the resistance threshold and up to and beyond the recovery threshold – as opposed to a risk approach which often focusses on design events derived from relatively short data records. Unexpected, extreme events can always happen because of inherent uncertainties in system behaviour and climate variability, and increasingly paleoclimate and paleohydrological studies point to extreme weather events in the past that are not taken into account in current infrastructure design (Knox and Kundzewicz, 1997; Wasson, 2016). At the same time climate change may increase variability and lead to new extremes. For instance, Räsänen et al. (2013) find that in the Mekong river basin the variability between droughts and floods in the post 1950 epoch is much higher compared to any of the other epochs since 1300.

Considering beyond-design events in disaster management could be called “possibilistic” thinking (Clarke, 2008), which is a complement to the “probabilistic” thinking commonly employed in the risk approach. It stimulates thinking about the worst case, or even unimaginable scenarios. In disaster risk management this is not yet common practice, though, for instance, in dam safety design it is often incorporated: dams are built from a functional perspective (power generation, irrigation storage, and/or flood storage) and operation rules are designed accordingly while taking into account climate variability. However, to prevent catastrophic failure, most dams also have spillways, which may be deployed in case of a threat of dam collapse due to beyond-design events.

Looking at beyond-design events does not mean only looking at the most extreme events. The Mississippi example in the previous section shows that additional measures – inundate rural areas by intentionally breaking levees – were deployed when the flood exceeded the levee's design criterion of a 100-year flood. The multiple-tiered approach for flood risk management in the Netherlands also explicitly considers beyond-design events by also aiming to reduce the consequences of flooding through spatial planning and by planning for evacuation (van Herk et al., 2014). On the other hand, drought risk management is typically reactive and

few places have plans in place to deal with a lack of water (Wilhite et al., 2014).

4.3. Design and prepare systems according to the 'remain functioning' principle

'Remain functioning' refers to designing systems in such a way that consequences of failure are not catastrophic, but manageable. This principle is also known as fail-safe, as opposed to safe-fail systems where the focus is on high reliability (Hashimoto et al., 1982; Jones et al., 1975). Making sure that a system remains functioning during extreme events acknowledges the fact that the possibility of failure cannot be eliminated altogether, and is typical for resilience thinking. In the context of extreme weather events, a requirement for systems to remain functioning is that critical infrastructure remains in service. If critical infrastructure is damaged, emergency management will be more difficult, recovery will be slower and impacts may spread to non-affected areas (De Bruijn et al., 2016). An example where critical infrastructure failed is the 2010 earthquake in Chile. Although Chile is very well prepared for earthquakes, the communication network almost completely broke down, ultimately resulting in widespread looting and anxiety (ARUP, 2014).

Emergency and crisis managers have always had ample attention for critical infrastructure in order to provide first response – and they often have dedicated emergency response infrastructure – though in case of extreme weather risk management attention for critical infrastructure is of a more recent date. Initiatives such as the Critical Infrastructure Preparedness and Resilience Research Network (www.ciprnet.eu) bring together knowledge to support authorities in protecting critical infrastructure and tools are being developed to analyse and better understand the cascading effects of failure of critical infrastructure due to flood events (e.g. Burzel et al., 2014). Governments increasingly carry out assessments and take measures to protect critical infrastructure. For instance, the Pitt Review following the UK floods of 2007 advised to protect critical infrastructure such as power and water supply, and main roads; recommendation numbers 50 to 54 appeal for a systematic program to reduce the disruption of essential services (Pitt, 2008 p. 417). Another example is the Port of Amsterdam which carried out a pilot study of critical functions and infrastructure (MUST and Witteveen + Bos, 2013).

It should be noted that well before the recent attention for critical infrastructure, the remain functioning principle has been applied by many societies in preparation for extreme weather events for a long time. The construction of roads on top of levees is a typical example that can be found in many floodplains around the world.

4.4. Increase the recovery capacity

The long-term impact of an event partly depends on the time it takes to recover, which in turn depends on the recovery capacity. Recovery capacity is often related to the general socio-economic level of society, referring to system characteristics that influence the ease with which a system recovers. Recovery capacity is thus a function of social capital (the individual ability of people to recover), institutional capital (the ability to organise repair and reconstruction), and economic capital (the ability to finance repair and reconstruction) (De Bruijn, 2005).

Increasing recovery capacity is thus closely linked to socio-economic development level, and hence measures are generally not specific for dealing with extreme weather events. Poverty alleviation, health improvement and education are sustainable development objectives that also increase a society's recovery

capacity. Yet some specific measures can target to increase the speed of recovery from extreme weather events. Insurance can provide disaster-affected households with the financial means for recovery and is used or considered in developed (Botzen et al., 2009; Petrolia et al., 2013; Penning-Rowsell et al., in press) as well as developing countries (Akter et al., 2009; Janzen and Carter 2013). Other financial assistance, such as loans, relief grants and reconstruction employment schemes can also increase the recovery capacity, as shown in Andhra Pradesh, India, after a cyclone (Marchand, 2009). Social capital for recovery can be improved by education and training as part of disaster preparedness programs. A study after floods in Pakistan showed that knowledge on recovery priorities positively affected the recovery (Asgary et al., 2012).

4.5. Remain resilient into the future

Flexibility, the ability to learn, the capacity to adapt and the willingness to transform if necessary are crucial to cope with gradual but uncertain changes. It is important to realise that the current resilience of a system may be exhausted due to gradual geo-physical developments such as climate change or subsidence, and socio-economic developments such as migration, conflicts, urbanisation and economic growth. This may call for adaptation or transformation in order to be able to cope with future extreme weather. In order to improve the capacity to adapt, institutions may have to change their culture and the way they are organised in order to enhance their ability to learn from previous experiences, to change and to improve themselves.

In addition to flexible, adaptive organizations, also flexible, adaptive policies and systems are required. Several tools, strategies and methods have been developed to help policymakers design

such policies and systems (Hallegatte 2009; Swanson et al., 2010; Walker et al., 2013). Examples of tools are adaptation pathways (Haasnoot et al., 2013), relying on the identification of policy tipping points to establish when policies can no longer meet the societal objectives and on the mapping of possible alternative strategies, and adaptive policy making (Walker et al., 2001), which is a generic procedure for developing robust plans. This type of tools contains feedback loops that trigger adaptations if elements of the system change. For instance, the Singapore government has introduced a resilience framework that explicitly acknowledges that understanding of climate change is continuously evolving, and that plans may need to be adapted (NCCS, 2012). The framework has a feedback loop so that future learning can be incorporated and adaptation plans are designed in a flexible manner.

The development of long-term, adaptive strategies is still an emerging research area, and will need to address evaluation criteria such as 'the least likelihood of regret' and 'equity between subareas, population groups, or generations', and methods to cope with uncertainties. Scenario-analysis, exploratory modelling and adaptation pathways can help define the most desirable adaptation measures, adaptation rates and windows to initiate a transition to an entirely different policy. Practical experience with the implementation of such methods is still scarce. It is expected that in the near future more approaches become operational for policy makers.

5. Applying the principles: two examples

In this section we give two examples that demonstrate the added value of the five principles in the management of extreme weather events. The first case discusses flood risk management in a

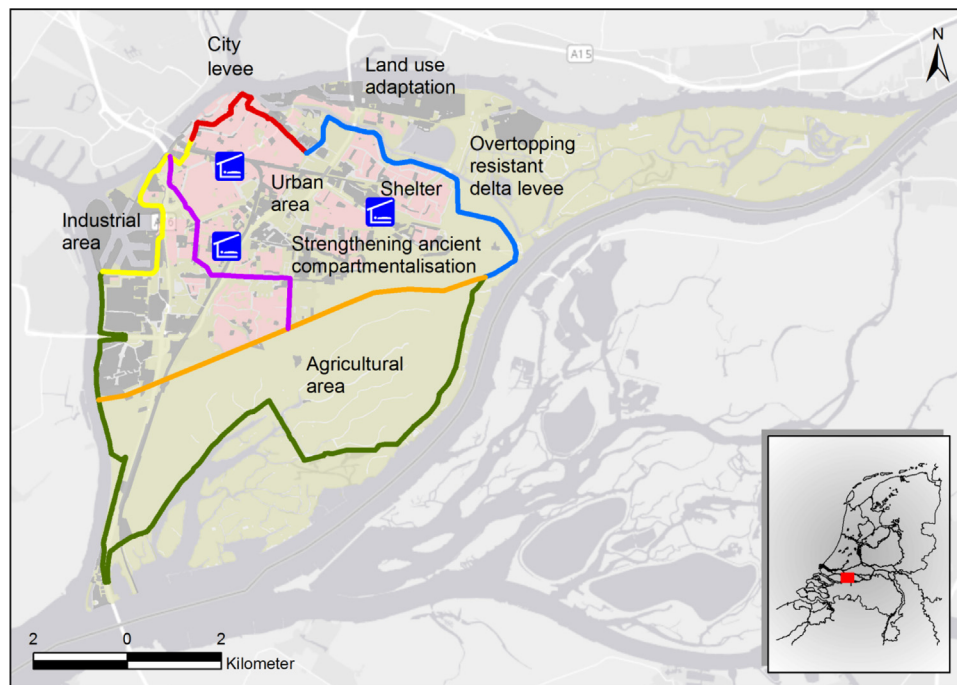


Fig. 1. Overview of the municipality of Dordrecht and the flood risk management strategy proposed. The blue, red, yellow and green lines are river embankments. The blue embankment is to be made overtopping resistant. The purple and orange lines indicate ancient embankments which may be strengthened to limit the flood extent due to potential floods from the south and west. Three shelters in the north eastern part can accommodate refugees from the western part if the embankment breaches there (derived from Lips, 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

municipality in the Netherlands. The second case discusses drought risk management in a river basin in Vietnam.

5.1. Flood risk management strategy in Dordrecht, the Netherlands

Dordrecht is a municipality in the tidal area of the Rhine-Meuse delta in the Netherlands. It is surrounded by rivers and canals, see Fig. 1. The old city centre and some industrial and residential areas are located outside embankments and are subject to flooding on average once every 10 years, though flooding depths are limited, generally up to about 20 centimetres. The embanked areas, when flooded, could experience flood depths of up to 2 m. A risk-based approach was adopted for flood protection following a large flooding of the southwest of the Netherlands in 1953. Currently, all embankments have to meet flood protection standards that were derived from risk analyses in the 1960s (Kind, 2014), which is for Dordrecht a protection against a once in 2000 years flood level.

New flood protection standards have been implemented in the new Water Act on the 1st of January 2017. In addition to an economic cost-benefit analysis (Kind, 2014), the new standards are based on an individual flood fatality hazard to account for equity (i.e. every inhabitant should have a risk of death from a flood event no greater than 0.00001 per year) and group flood fatality risk to account for societal disruption (assessed as the probability of a large number of casualties in a single event) (De Bruijn et al., 2014, 2015). The calculations for the new flood protection standards take into account the whole flood protection system in the Netherlands: dependencies between different flood-prone areas and embankment sections are taken into account in order to analyse how many breaches might occur in one event (De Bruijn et al., 2014). Also, the new flood protection standards take into account the impacts beyond the embankment design criteria to some extent, by considering potential numbers of casualties. the 'remain functioning' principle for critical infrastructure. However, in practice only the gas extraction and supply system was considered in the discussion on safety standards. The new Water Act does not include any reference to the principle 'increase recovery capacity'. The Netherlands did attempt to explore future adaptation in the Adaptive Delta Management approach (Klijn et al., 2016) but this had no implications yet for the current flood protection standards or policies in Dordrecht.

That adopting the five resilience principles would result in different flood risk management strategies can be illustrated by a case study of the island of Dordrecht (based on De Bruijn et al., 2016). The case study adopted a systems approach rather than optimising flood protection levels for each location separately and it considered the whole chain of events from the first flood forecasts to the post-flood recovery. The approach taken was to develop storylines for a set of representative potential breach locations. The status of flood protection infrastructure, critical infrastructure and the responses of the local authorities and inhabitants of the area were described for different points in time based on protocols, experience and assumptions, which were discussed in workshops. Models were used to simulate flood propagation, damage, casualties and the whereabouts of people on the island, including how many people moved to safe areas.

The case study contributed to the design of a resilient flood risk management strategy combining different types of measures. The embankments remain the first line of defence to resist floods. Embankment strengthening was recommended at several locations; for one section it was recommended to make the embankment able to cope with overtopping (fail-safe, rather than accepting that it fails due to erosion resulting from overtopping) – a resilience measure acknowledging the possibility of beyond-design events, see Fig. 1. Other measures to deal with beyond-design events included emergency drainage,

compartmentalisation through strengthening and maintenance of secondary embankments inside the polder area, and emergency response measures, such as construction of shelters. Developing better emergency plans and measures to increase the people's preparedness can reduce the number of casualties and significantly enhance recovery. The analysis of critical infrastructure in the storylines provided, for instance, insights into the actions of the electricity supply company regarding cutting off and restoring power, and how this affected other systems. The analysis did not specifically establish how the municipality can remain resilient in the future.

The case study shows that considering the whole system and the whole chain of events instead of just looking at the maximum water depth or at one location results in a more comprehensive set of measures, not only increasing the resistance, but also the resilience in view of beyond-design events. However, the case study focused on the interests of the emergency managers and water board and hence did not look at other relevant measures that others could take, such as changing designs or operations of critical infrastructure or adapting land use in the non-protected areas. In that respect, it is still a partial strategy as not all potential actors (all systems and subsystems) were involved.

5.2. Drought risk management in the Vu Gia – Thu Bon river basin

The Vu Gia – Thu Bon (VGTB) river basin is located in central Vietnam. The western part of the basin is mountainous and sparsely populated, while the flat delta area in the east, covering about one fifth of the basin area, is dominated by agriculture and urban development. Numerous reservoirs and weirs are located in the basin irrigating over 30,000 ha of rice and 10,000 ha of subsidiary crops and cash-crop trees. Hydropower is developing rapidly. Droughts are common in the area; 2005, 2013 and 2016 were the most recent dry years. Here we focus on the resilience of agricultural households facing droughts. Information for this case was obtained from a survey among 383 households, interviews with four different government agencies (responsible for respectively urban water supply, agriculture, environment and industry) and a review of secondary literature (Buurman et al., 2016).

Drought risk management in the basin so far focused on developing irrigation infrastructure, and to a limited extent on providing the farming households with information on when a drought is foreseen and which actions could be taken, such as postpone planting or change crops. There is no drought risk management plan for the area. This brief example gives some considerations in developing a more resilient, largely agricultural, society in response to droughts.

A system's approach considers the entire basin and all physical, biological and human characteristics and activities in it. Important activities or sectors which need to be considered in this case are hydropower generation, irrigation for agriculture, and their relation with security of water, food and power supply for both urban and rural citizens. Upstream-downstream interactions are relevant as the development of hydropower upstream affects water allocation in the entire basin, and reportedly increases downstream impacts of droughts. From the perspective of agricultural households, farming is a source of income as well as a source of food. Based on information from the survey, key factors for society related to water availability are costs of groundwater pumping, irrigation fees, costs of health impacts, and costs of additional effort and labour due to droughts, in addition to loss of income. Additional dissemination of drought information and community drought response should be considered as well, when developing strategies. Salt intrusion, water quality and bank erosion are characteristics of the physical system related to droughts which affect the socio-economic system. In

Vietnam also the institutional and governance system is crucial and complex, since it includes at least ten agencies.

The current irrigation and water supply system in the basin is rather robust for moderate droughts. Yet, severe droughts could lead to large numbers of households having no access to water for agriculture and household supply. Critical infrastructure is not directly affected by droughts. Only the Danang city urban water supply system is currently already affected by moderate droughts and interventions are being considered to increase the capacity of the system with new dams and intake points. Hydropower generation is also vulnerable to droughts. For the 2013 (medium) drought households reported losses in the order of 15–60% of their annual incomes due to drought impacts.

The five resilience principles discussed in Section 4 can support the development of sustainable strategies to enable the different social groups (farmers/citizens) to cope with droughts. The relevant sectors (irrigation, hydropower, agriculture, sanitation) need to be considered in an interrelated way in a systems approach and interests should be balanced. Although the focus may be on the more frequently expected drought situations, possibilistic thinking could help to consider what could be done to best cope with extreme droughts. If there is too little water for irrigation, hydropower and sanitation, damage may occur, but actions should be taken to prevent collapse of structures or other long-term effects. Permanent crops or, for example, the integrity of reservoirs should be given priority and people should not be forced to use destructive strategies such as selling income-generating assets. Strategies could aim to improve recovery by, for example, providing access to loans or by providing support for repair, providing seeds and by immediately repairing roads and other critical infrastructure. Weather-index insurances could be considered as a measure to increase recovery capacity. Remaining resilient into the future requires government policies that incorporate learning and adaptation. Drought policies and plans should be regularly reviewed and institutional innovation encouraged. Households should be enabled to adapt over time. These are complex issues that require thorough analysis and long-term commitments.

6. Conclusions

Resilience is an ambiguous concept and is interpreted differently by different people. Yet, putting the conceptual discussion aside, five main notions of resilience can be defined for dealing with extreme weather events and these main notions can be translated into five practical resilience principles to support decision-making and disaster risk reduction policies. Applying these principles in practice will aid in developing strategies and designing adaptive pathways into the future which make the physical-societal system more resilient to extreme weather events such as floods and droughts. The principles encourage taking a whole-systems approach, considering beyond-design events, making sure the system can remain functioning under extreme events, considering system response and recovery, and acknowledging and including gradual future changes. Resilience advocates often point at one or more of these principles as they realise that these are being missed in many conventional risk-based management approaches. Although most of the principles are widely acknowledged and sometimes applied, resilience approaches are often disconnected from policy practice, or remain in the research domain without being translated into practice.

The examples of Dordrecht and the Vu Gia – Thu Bon river basin show that applying the resilience principles may turn a risk management strategy consisting of solely structural, protection-type interventions to a comprehensive strategy with additional preparedness and emergency response measures, spatial planning

instruments, and instruments that enhance a society's recovery capacity. Moreover, it allows making use of system behaviour, where measures in one part of the system may increase the coping capacity of the entire system, or where measures are clearly targeted to the needs of the societal system.

The resilience principles provide a useful translation of notions of resilience for policy makers. As societies face increasing complexity and uncertainty, decision making to cope with extreme weather events should evolve from an oversimplified risk approach to a much richer resilience approach. This requires further development of resilience-based models and frameworks, additional decision criteria beyond common cost-benefit related criteria, as well as communicating these with policy makers.

References

- ADB, 2014. Urban Climate Change Resilience: A Synopsis. Asian Development Bank, Manila.
- ARUP, 2014. City Resilience Framework. ARUP & The Rockefeller Foundation.
- Adger, W.N., 2000. Social and ecological resilience: are they related? *Prog. Hum. Geogr.* 24, 347.
- Aerts, J.C.J.H., Botzen, W., van der Veen, A., Kryukow, J., Werners, S., 2008. Dealing with uncertainty in flood management through diversification. *Ecol. Soc.* 13 (1) [online] URL: <http://www.ecologyandsociety.org/vol13/iss1/art41/n.2008>.
- Akter, S., Brouwer, R., Choudhury, S., Aziz, S., 2009. Is there a commercially viable market for crop insurance in rural Bangladesh? *Mitig. Adapt. Strategies Glob. Change* 14, 215–229. doi:<http://dx.doi.org/10.1007/s11027-008-9161-6>.
- Asgary, A., Anjum, M.I., Azimi, N., 2012. Disaster recovery and business continuity after the 2010 flood in Pakistan: case of small businesses. *Int. J. Disaster Risk Reduct.* 2, 46–56. doi:<http://dx.doi.org/10.1016/j.ijdr.2012.08.001>.
- Béné, C., Cannon, T., Gupta, J., Mehta, L., Tanner, T., 2014. Exploring the Potential and Limits of the Resilience Agenda in Rapidly Urbanising Contexts. Institute of Development Studies.
- Berkes, F., Ross, H., 2016. Panarchy and community resilience: sustainability science and policy implications. *Environ. Sci. Policy* 61, 185–193. doi:<http://dx.doi.org/10.1016/j.envsci.2016.04.004>.
- Biggs, R., et al., 2012. Toward principles for enhancing the resilience of ecosystem services. *Annu. Rev. Environ. Resour.* 37, 421–448. doi:<http://dx.doi.org/10.1146/annurev-environ-051211-123836>.
- Botzen, W.J.W., Aerts, J.C.J.H., van den Bergh, J.C.J.M., 2009. Willingness of homeowners to mitigate climate risk through insurance. *Ecol. Econ.* 68, 2265–2277. doi:<http://dx.doi.org/10.1016/j.ecolecon.2009.02.019>.
- Bubeck, P., Botzen, W.J.W., Aerts, J.C.J.H., 2012. A review of risk perceptions and other factors that influence flood mitigation behavior. *Risk Anal.* 32, 1481–1495. doi:<http://dx.doi.org/10.1111/j.1539-6924.2011.01783.x>.
- Burns, Z., et al., 2010. Overweighting of small probabilities. *Wiley Encyclopedia of Operations Research and Management Science*. John Wiley & Sons, Inc. doi:<http://dx.doi.org/10.1002/9780470400531.eorms0634>.
- Burzel, A., Hounjet, M., Becker, B., Di Pietro, A., Pollino, M., Rosato, V., Tofani, A., 2014. Towards a decision support system for consequence analysis of flooding on critical infrastructure. Paper Presented at the 11th International Conference on Hydroinformatics, New York, 17–21 August 2014.
- Buurman, J., Bui, D.D., Du, L.T.T., (2016) Drought risk assessment by combining household survey information and drought indicators: a case study in central Vietnam Submitted.
- Carpenter, S., Walker, B., Anderies, M.J., Abel, N., 2001. From metaphor to measurement: resilience of what to what? *Ecosystems* 4, 765–781. doi:<http://dx.doi.org/10.1007/s10021-001-0045-9>.
- Clarke, L., 2008. Possibilistic thinking: a new conceptual tool for thinking about extreme events. *Soc. Res.* 75, 669–690.
- Crowe, P.R., Foley, K., Collier, M.J., 2016. Operationalizing urban resilience through a framework for adaptive co-management and design: five experiments in urban planning practice and policy. *Environ. Sci. Policy* 62, 112–119. doi:<http://dx.doi.org/10.1016/j.envsci.2016.04.007>.
- Cumiskey, L., Werner, M., Meijer, K., Fakhruddin, S.H.M., Hassan, A., 2015. Improving the social performance of flash flood early warnings using mobile services. *Int. J. Disaster Resil. Built Environ.* 6, 57–72. doi:<http://dx.doi.org/10.1108/ijdrbe-08-2014-0062>.
- Davoudi, S., 2012. Resilience: a bridging concept or a dead end? *Plann. Theory Pract.* 13, 299–307. doi:<http://dx.doi.org/10.1080/14649357.2012.677124>.
- De Bruijn, K.M., Diermanse, F.L.M., Beckers, J.V.L., 2014. An advanced method for flood risk analysis in river deltas, applied to societal flood fatality risk in the Netherlands. *Nat. Hazards Earth Syst. Sci.* 14, 2767. doi:<http://dx.doi.org/10.5194/nhess-14-2767-2014>.
- De Bruijn, K.M., Klijn, F., van de Pas, B., Slager, C.T.J., 2015. Flood fatality hazard and flood damage hazard: combining multiple hazard characteristics into meaningful maps for spatial planning. *Nat. Hazards Earth Syst. Sci.* 15, 1297–1309. doi:<http://dx.doi.org/10.5194/nhess-15-1297-2015>.
- De Bruijn, K.M., Lips, N., Gersonius, B., Middelkoop, H., 2016. The storyline approach: a new way to analyse and improve flood event management. *Nat. Hazards* 81, 99–121. doi:<http://dx.doi.org/10.1007/s11069-015-2074-2>.

- De Bruijn, K.M., 2004. Resilience and flood risk management. *Water Policy* 6, 53–66.
- De Bruijn, K.M., 2005. Resilience and Flood Risk Management. A Systems Approach Applied to Lowland Rivers. Delft University of Technology.
- Dilley, P., 2016. Environment Agency Head Calls for Focus on Resilience. <http://www.building.co.uk/environment-agency-head-calls-for-focus-on-resilience/5079494.article>.
- Douven, W., et al., 2012. Resistance versus resilience approaches in road planning and design in delta areas: mekong floodplains in Cambodia and Vietnam. *J. Environ. Plann. Manage.* 55, 1289–1310. doi:<http://dx.doi.org/10.1080/09640568.2011.644848>.
- EU, (2013) The EU Strategy on adaptation to climate change.
- Fan, L., 2013. Disaster as Opportunity? Building Back Better in Aceh, Myanmar and Haiti. Humanitarian Policy Group, Overseas Development Institute, London.
- Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T., Rockstrom, J., 2010. Resilience thinking: integrating resilience, adaptability and transformability. *Ecol. Soc.* 15.
- Folke, C., 2006. Resilience: the emergence of a perspective for social-ecological systems analyses. *Global Environ. Change* 16, 253–267. doi:<http://dx.doi.org/10.1016/j.gloenvcha.2006.04.002>.
- Funfgeld, H., McEvoy, D., 2012. Resilience as a useful concept for climate change adaptation? *Planning Theory & Practice* 13, 324–328. doi:<http://dx.doi.org/10.1080/14649357.2012.677124>.
- Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Global Environ. Change* 23, 485–498. doi:<http://dx.doi.org/10.1016/j.gloenvcha.2012.12.006>.
- Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. *Global Environ. Change* 19, 240–247. doi:<http://dx.doi.org/10.1016/j.gloenvcha.2008.12.003>.
- Haraguchi, M., Lall, U., 2015. Flood risks and impacts: a case study of Thailand's floods in 2011 and research questions for supply chain decision making. *Int. J. Disaster Risk Reduct.* 14 (Part 3), 256–272. doi:<http://dx.doi.org/10.1016/j.ijdr.2014.09.005>.
- Hashimoto, T., Stedinger, J.R., Loucks, D.P., 1982. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res.* 18, 14–20. doi:<http://dx.doi.org/10.1029/wr018i001p00014>.
- Holling, C.S., 1973. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* 4, 1–23. doi:<http://dx.doi.org/10.1146/annurev.es.04.110173.000245>.
- Holling, C.S., 1996. Engineering resilience versus ecological resilience. In: Schulze, P. (Ed.), *Engineering Within Ecological Constraints*. National Academy Press, Washington, pp. 31–44.
- Janzen, S.A., Carter, M.R., 2013. After the Drought: The Impact of Microinsurance on Consumption Smoothing and Asset Protection. National Bureau of Economic Research, Cambridge.
- Jones, D.D., Holling, C.S., Peterman, R., 1975. Fail-safe Vs. Safe-fail Catastrophes. International Institute for Applied Systems Analysis, Laxenburg.
- Jonkman, S.N., van Gelder, P.H.A.J.M., Vrijling, J.K., 2003. An overview of quantitative risk measures for loss of life and economic damage. *J. Hazard. Mater.* 99, 1–30. doi:[http://dx.doi.org/10.1016/S0304-3894\(02\)00283-2](http://dx.doi.org/10.1016/S0304-3894(02)00283-2).
- Kahneman, D., Tversky, A., 1979. Prospect theory: an analysis of decision under risk. *Econometrica* 47, 263–291. doi:<http://dx.doi.org/10.2307/1914185>.
- Kenny, C., 2012. Disaster risk reduction in developing countries: costs, benefits and institutions. *Disasters* 36, 559–588. doi:<http://dx.doi.org/10.1111/j.1467-7717.2012.01275.x>.
- Kind, J.M., 2014. Economically efficient flood protection standards for the Netherlands. *J. Flood Risk Manage.* 7, 103–117. doi:<http://dx.doi.org/10.1111/jfr3.12026>.
- Klijn, F., Asselman, N., van der Most, H., 2010. Compartmentalisation: flood consequence reduction by splitting-up large polder areas. *J. Flood Risk Manage.* 3 (2010), 3–17. doi:<http://dx.doi.org/10.1111/j.1753-318x.2009.01047.x>.
- Klijn, F., Kreibich, H., de Moel, H., Penning-Rowell, E., 2015. Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation. *Mitig. Adapt. Strategies Glob. Change (MITI)* 20 (2015/6), 845–864. doi:<http://dx.doi.org/10.1007/s11027-015-9638-z>.
- Klijn, F., Asselman, N.E.M., de Kruijff, A., Bloemen, P.J.T.M., Haasnoot, M., 2016. Implementing new flood protection standards: obstacles to adaptive management and how to overcome these. *FLOODrisk 2016*, 3rd European Conference on Flood Risk Management, Innovation, Implementation, Integration October 2016, Lyon, France, pp. 18–20. doi:<http://dx.doi.org/10.1051/e3sconf/20160721003>.
- Knox, J.C., Kundzewicz, Z.W., 1997. Extreme hydrological events, palaeo-information and climate change. *Hydrol. Sci. J.* 42, 765–779. doi:<http://dx.doi.org/10.1080/0262669709492071>.
- Kunreuther, H.C., 1980. Decision Making for Low Probability Events: A Conceptual Framework. International Institute for Applied Systems Analysis, Laxenburg.
- Linkov, I., et al., 2014. Changing the resilience paradigm. *Nat. Clim. Change* 4, 407–409. doi:<http://dx.doi.org/10.1038/nclimate2227>.
- Lyons, M., 2009. Building back better: the large-scale impact of small-scale approaches to reconstruction. *World Dev.* 37, 385–398. doi:<http://dx.doi.org/10.1016/j.worlddev.2008.01.006>.
- MOIE, 2015. Delta Programme 2016: Work on the Delta. The Hague.
- MUST, Witteveen + Bos (2013) Waterbestendige Westpoort - Pilotstude vitiaal en kwetsbare functies in de haven van Amsterdam.
- Manyena, S.B., O'Brien, G., O'Keefe, P., Rose, J., 2011. Disaster resilience: a bounce back or bounce forward ability? *Local Environ.* 16, 417–424. doi:<http://dx.doi.org/10.1080/13549839.2011.583049>.
- Marchand, M., 2009. Modelling Coastal Vulnerability: Design and Evaluation of a Vulnerability Model for Tropical Storms and Floods. Technical University Delft.
- Masozera, M., Bailey, M., Kerchner, C., 2007. Distribution of impacts of natural disasters across income groups: a case study of New Orleans. *Ecol. Econ.* 63, 299–306. doi:<http://dx.doi.org/10.1016/j.ecolecon.2006.06.013>.
- McDaniels, T., Chang, S., Cole, D., Mikawoz, J., Longstaff, H., 2008. Fostering resilience to extreme events within infrastructure systems: characterizing decision contexts for mitigation and adaptation. *Global Environ. Change* 18, 310–318. doi:<http://dx.doi.org/10.1016/j.gloenvcha.2008.03.001>.
- Meadows, D.H., 2008. *Thinking in Systems: a Primer*. Chelsea Green Publishing, Vermont.
- Mens, M.J.P., Klijn, F., de Bruijn, K.M., van Beek, E., 2011. The meaning of system robustness for flood risk management. *Environ. Sci. Policy* 14, 1121–1131. doi:<http://dx.doi.org/10.1016/j.envsci.2011.08.003>.
- Merz, B., Hall, J., Disse, M., Schumann, A., 2010a. Fluvial flood risk management in a changing world. *Nat. Hazards Earth Syst. Sci.* 10, 509–527.
- Merz, B., Kreibich, H., Schwarze, R., Thieken, A., 2010b. Review article Assessment of economic flood damage. *Nat. Hazards Earth Syst. Sci.* 10, 1697–1724. doi:<http://dx.doi.org/10.5194/nhess-10-1697-2010>.
- Milkoreit, M., Moore, M.-L., Schoon, M., Meek, C.L., 2015. Resilience scientists as change-makers—growing the middle ground between science and advocacy? *Environ. Sci. Policy* 53, 87–95. doi:<http://dx.doi.org/10.1016/j.envsci.2014.08.003>.
- Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Stationarity is dead: whither water management? *Science* 319, 573–574. doi:<http://dx.doi.org/10.1126/science.1151915>.
- NCCS, 2012. Climate change & Singapore: challenges. Opportunities. Partnerships. National Climate Change Secretariat. Prime Minister's Office, Singapore.
- Newell, B., Wasson, R., 2002. Social system versus solar system: why policy makers need history. Paper Presented at the International Water History Association's Conference on The Role of Water in History and Development, Bergen, Norway, 10–12 August.
- Olson, K.R., Morton, L.W., 2012. The effects of 2011 Ohio and Mississippi river valley flooding on Cairo, Illinois, area. *J. Soil Water Conserv.* 67, 42A–46A. doi:<http://dx.doi.org/10.2489/jswc.67.2.42a>.
- Olsson, L., Jerneck, A., Thoren, H., Persson, J., O'Byrne, D., 2015. Why resilience is unappealing to social science: theoretical and empirical investigations of the scientific use of resilience. *Sci. Adv.* 1 doi:<http://dx.doi.org/10.1126/sciadv.1400217>.
- Pendall, R., Foster, K.A., Cowell, M., 2010. Resilience and regions: building understanding of the metaphor. *Cambridge Journal of Regions. Econ. Soc.* 3, 71–84. doi:<http://dx.doi.org/10.1093/cjres/rsp028>.
- Penning-Rowell, E.C., Priest, S., Johnson, C., (in press 2014). The evolution of UK flood insurance: Incremental change over six decades. *International Journal of Water Resources Development (Accepted 7 March 2014)*.
- Petrolia, D.R., Landry, C.E., Coble, K.H., 2013. Risk Preferences. *Risk Percep. Flood Insurance Land Econ.* 89, 227–245.
- Pitt, M., 2008. Learning Lessons from the 2007 Floods. .
- Räsänen, T.A., Lehr, C., Mellin, I., Ward, P.J., Kumm, M., 2013. Palaeoclimatological perspective on river basin hydrometeorology: case of the Mekong Basin. *Hydrol. Earth Syst. Sci.* 17, 2069–2081. doi:<http://dx.doi.org/10.5194/hess-17-2069-2013>.
- Restemeyer, B., Woltjer, J., van den Brink, M., 2015. A strategy-based framework for assessing the flood resilience of cities – a Hamburg case study. *Plann. Theory Pract.* 16, 45–62. doi:<http://dx.doi.org/10.1080/14649357.2014.1000950>.
- Roberts, E., Andrei, S., Huq, S., Flint, L., 2015. Resilience synergies in the post-2015 development agenda. *Nat. Clim. Change* 5, 1024–1025. doi:<http://dx.doi.org/10.1038/nclimate2776>.
- Shaw, K., 2012. Reframing resilience: challenges for planning theory and practice. *Planning Theory Pract.* 13, 308–312. doi:<http://dx.doi.org/10.1080/14649357.2012.677124>.
- Simonović, S.P., 2011. *Systems Approach to Management of Disasters: Methods and Applications*. Wiley, New Jersey doi:<http://dx.doi.org/10.1002/9780470890363>.
- Slovic, P., Fischhoff, B., Lichtenstein, S., Corrigan, B., Combs, B., 1977. Preference for insuring against probable small losses: insurance implications. *J. Risk Insurance* 44, 237–258. doi:<http://dx.doi.org/10.2307/252136>.
- Swanson, D., et al., 2010. Seven tools for creating adaptive policies. *Technol. Forecast. Social Change* 77, 924–939. doi:<http://dx.doi.org/10.1016/j.techfore.2010.04.005>.
- UNISDR, 2004. *Living with Risk: A Global Review of Disaster Reduction Initiatives*. United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction, New York and Geneva.
- UNISDR, 2009. *UNISDR Terminology on Disaster Risk Reduction*. United Nations. International Strategy for Disaster Reduction, Geneva.
- Van der Most, H., Tanczos, I., De Bruijn, K.M., Wagenaar, D., 2014. New, risk-based standards for flood protection in the Netherlands. Paper Presented at the 6th International Conference on Flood Management, Sao Paulo, Brazil, September 2014.
- Walker, W.E., Rahman, S.A., Cave, J., 2001. Adaptive policies, policy analysis, and policy-making. *Eur. J. Oper. Res.* 128, 282–289. doi:[http://dx.doi.org/10.1016/S0377-2217\(00\)00071-0](http://dx.doi.org/10.1016/S0377-2217(00)00071-0).
- Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A., 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecol. Soc.* 9.
- Walker, W., Haasnoot, M., Kwakkel, J., 2013. Adapt or perish: a review of planning approaches for adaptation under. *Deep Uncertain. Sustain.* 5, 955–979.

- 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. *Technol. Forecast. Soc. Change* 77, 987–998. doi:<http://dx.doi.org/10.1016/j.techfore.2009.11.005>.
- Wasson, R.J., 2016. Uncertainty, ambiguity and adaptive flood forecasting. *Policy Soc.* doi:<http://dx.doi.org/10.1016/j.polsoc.2016.06.002>.
- Wilhite, D.A., Sivakumar, M.V.K., Pulwarty, R., 2014. Managing drought risk in a changing climate: the role of national drought policy. *Weather Clim. Extremes* 3, 4–13. doi:<http://dx.doi.org/10.1016/j.wace.2014.01.002>.
- van Herk, S., Zevenbergen, C., Gersonius, B., Waals, H., Kelder, E., 2014. Process design and management for integrated flood risk management: exploring the multi-layer safety approach for Dordrecht, The Netherlands. *J. Water Clim. Change* 5, 100–115. doi:<http://dx.doi.org/10.2166/wcc.2013.171>.