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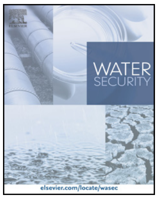

Exploring the relation between flood risk management and flood resilience

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ABSTRACT

Flood risk management has proven successful at reducing the threat of some flooding hazards, preventing loss of life during flooding events and easing the economic burden to communities and regions following floods. It is a useful approach for assessing risks and guiding decisions on implementing protection measures. Recently, in addition to flood risk management, flood resilience is discussed as a new approach in academic literature. This contribution tries to unravel the relation between flood risk management and flood resilience. Therefore, three aspects are discussed: the definition of resilience, its measurement methods and also its possible implementation and embedding in flood risk management.

1. Introduction

Resilience is a relatively new concept as applied to environmental hazard management [2]. Currently, a risk-based approach is dominating the way society deals with natural hazards, such as floods. Whereas the risk-based approach provides a rational way of balancing the costs of mitigation and adaptation measures [38], resilience embraces the uncertainties associated with natural hazards by focusing on the ability of affected systems to absorb shocks [33].

The idea of resilience follows closely with a modern emphasis on integrated solutions to environmental issues which are becoming increasingly complex as they expand geographically, economically, socially and politically. At the same time, resilience is considered to be too abstract, apolitical and ahistorical in social science [49]. The traditional ways of applying measures which consider closed and simplified boundary conditions are no longer adequate. In a modern world, processes and people are highly dynamic and far-reaching. Therefore, our measures must reflect society by learning to become similarly flexible and inclusive.

It is no simple task, however, as the direction toward the implementation of resilience concepts is hazy at best [32]. Consider for example the difficulty of simultaneously implementing the concept's seemingly opposing properties of stability and adaptation in unison [32,54]. Resilience supports to some extent a "bouncing back" to a previous state of a system. This promotes a notion of stability of the state of a system. At the same time, resilience also embraces adaption, or "bouncing forward." This seeming contradiction of stability and adaptation is embedded in the term resilience and creates fuzziness in regard to the concept. When difficult, but important goals are born from unclear concepts, terms which are paramount to understanding a new directional shift can become buzzwords, lacking concrete meaning [39,41].

Resilience, in its most general interpretation as applied to flood management, seeks to reduce adverse impacts of extreme events, which can otherwise prove devastating for communities and potentially produce disasters. Therefore, it is important to improve the ambiguity associated with resilience, develop techniques for quantifying its state, and improve measures for its implementation.

The following work is broken into sections and subsections which allow for much larger topics to be organized and summarized in a clear and comprehensible way. First, a brief background and a review of the basic principles of flood risk management are provided, along with a discussion on the relation to flood resilience. Next, a review and discussion of current flood resilience literature is presented. This work is centered around three main thematic areas: conceptualizing resilience, measuring resilience and implementing resilience. By highlighting the current progress in regard to these themes, we hope to unravel the relation between flood risk management and flood resilience.

2. Flood risk management

Flood risk management has become a dominant approach in much of the world for addressing the potential consequences due to flooding events. It is, in fact, a vast improvement from traditional measures which had prevailed previously. Traditional methods can be characterized by structures built in an attempt to control rivers, largely

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ignoring vulnerability [43].

The European Floods Directive (2007/60/EC) [22] institutionalized an ongoing shift from this traditional approach of flood protection to a risk-based approach [30]. Within flood risk management a more differentiated protection is suggested. It implies taking different risk levels into account and assessing and designing measures taking the potential damages into account – not only according to a design level regardless of the vulnerabilities [26,48]. Flood risk management emerged in Europe as a result of major flood events in the early 1990s at the Rhine River. It was institutionally embedded at the European level after major flooding events in 2002 at the Elbe River and its tributaries. It is still in a process of evolving out of the resistance culture from which it originated [46]. This leads to some important issues in the face of change which are likely to be further exploited in the coming years. A call to return to “living with rivers” in order to counteract the trend of resistance is gaining traction [58], but will require a long planning process to make this shift a reality [43].

Flood risk management has proven successful at reducing the threat of some flooding hazards, preventing loss of life during flooding events and easing the economic burden to communities and regions following floods. It is a useful tool for assessing risks and guiding decisions on how best to implement protection measures. However, in order to demonstrate the potential for strengthening the relation to flood resilience, the following sections provide theoretical background of flood risk management, present the ways in which resilience is only marginally applied in many flood risk management strategies, and discuss the differences in focus between the two strategies.

2.1. Review of terms and concept

The management of environmental risk centers around a singular principle as formulated by the risk equation (Fig. 1). Though the equation is seldom applied in its explicit form due to lack of data, imprecise estimates of some inputs or complexity compared to other satisfactory methods [34], it is upon this basic idea which specific applications of risk estimation are derived.

In environmental risk management, the *Probability* of interest is often the likelihood of a hazard event being exceeded in a given period. For example, the probability that a flooding event which exceeds a specified stage occurs in the course of a year. Accurate estimation of the probability density function for flooding hazards is difficult, but highly important. Ideally, a sufficiently long record of historical stage measurements in a relatively unchanging catchment would result in low uncertainties associated with the probability density function. However, even in the ideal case, the exceedance probability of extreme events is potentially impossible to estimate because of their long return periods [34].

Additionally, climate change may also increase the uncertainties associated with hazard probabilities due to its effects on stationarity. The principle of hazard stationarity allows for the critical assumption that environmental variables fluctuate within an unchanging envelope [44]. As climate change warms the earth, the resulting changes on environmental variables may render the assumption invalid. Though there is currently limited evidence of a change in global flood magnitudes and frequencies, there is higher confidence that heavy rainfall events will increase in frequency for many regions in the coming decades [34].

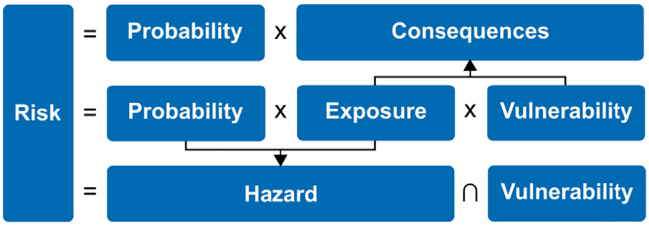

Fig. 1. Conceptualization of risk equation components and their relationship to one another, adapted from Klijn et al. [37].

Consequences, in the context of flood risk management, are the outcomes — typically adverse — should the flooding event of interest occur. For example, the cost of water damages to homes following an event. As Fig. 1 shows, this component can be considered as a combination of *Exposure* and *Vulnerability*.

According to the United Nations Office for Disaster Risk Reduction [57] (UNDRR), *Exposure* can be defined as “the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas.” Accurate determination of hazard-prone areas depends to a large extent on the ability to estimate and extrapolate hydrological variables as flood model inputs. The ability to derive the model inputs is, consequently, dependent on corresponding data availability. Additionally, data regarding assets in flood-prone areas is necessary, though more easily estimated through remote sensing and governmental sources. Management strategies related to removing people and assets from flood plains, including land-use management through zoning laws, for example, help to reduce exposure.

Likewise, UNDRR [57] defines *Vulnerability* as “the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.” The actual estimation and application of vulnerability is quite difficult in flood risk management and contributes a lot of uncertainty. Aerts [1] explains that damage functions correlating flood depth with potential damages to assets or loss of life are used to estimate vulnerability. Because this vulnerability curve is difficult to estimate, it is often empirically derived or based on expert opinions. It is further argued by Aerts [1] that this approach fails to adequately represent vulnerability because it is an oversimplified representation of human behavior, requiring greater input from social sciences. Vulnerability can be reduced, for example, physically through management strategies including wet- and dry-proofing buildings or socially by improving education about flood safety.

Vulnerability is often seen as the component of flood risk management most closely related with flood resilience. However, conceptual distinctions between the two terms are not universal. One position is that vulnerability and resilience are opposite attributes of the same system. For example, Twigg [55] describes vulnerability and resilience as two sides of the same coin, while conceding that both terms are also relative. This idea of opposite attributes, though clear, is overly simplistic. Therefore, others argue that the two terms are related, but remain distinct [18]. Twigger-Ross et al. [56] states, “Contrary to some conceptualizations where resilience and vulnerability are oppositional, we propose that there is overlap within these concepts [vulnerability and resilience] so that they are not totally mutually exclusive, nor totally mutually inclusive.” Additionally, it is argued that emphasizing resilience over vulnerability demonstrates what communities are able to do for themselves, rather than focusing on aspects which are weak in regard to floods [41,55].

2.2. Current applications of flood resilience measures in flood risk management

Flood risk management and flood resilience have the potential to act as strong complements to one another. However, in reality, resilience tends to be only marginally applied as a supplement to flood risk management. This section provides some brief examples of the ways in which flood resilience measures are used in current flood risk management strategies, in order to demonstrate the potential for greater emphasis and improvement.

Ashley et al. [4] and White et al. [61] describe some such examples of flood resilience methods as they appear in flood risk management policy. These strategies are often referred to by catchy acronyms and names, and applied as an addition to flood risk management, rather than taking an integral role in flood management policy.

The “Four A’s” approach, attributed to the Scottish government, is one such example. The strategy comprises: awareness (building knowledge among the community and committing flooding potential to memory), avoidance (removal of assets from flood prone areas), alleviation (flood-minded design of buildings; wet-proofing and dry-proofing) and assistance (insurance of assets or the infrastructure and plans associated with recovery and response efforts).

Another example identified is the “Four Capacities” approach, developed in the Netherlands. According to Graaf, Giesen and Ven [25], these four capacities include: threshold capacity (ability to resist floods), coping capacity (ability to reduce damage from flood exceeding damage threshold), recovery capacity (ability to restore losses after an event) and adaptive capacity (ability to apply a diversity of measures).

This review will demonstrate that flood resilience has more to offer and is more complex than what is condensed into these policies. It is important that flood resilience takes a less marginal role in future flood management and is viewed with equal standing with flood risk management for addressing flooding hazards, instead of a small addition to it.

2.3. *Focusing on recovery versus damage*

Flood risk management is primarily concerned with damage to assets. This approach to flood management is rather appealing due to the relatively easily defined and clearly established components. This is a method focused on the aspects of flood management which can be directly quantified (monetary value of an asset, such as a building or an automobile, for example), as opposed to the more qualitative aspects which can be difficult to quantify (sense of community, feeling of safety or diversity of included voices). Whereas flood risk management operates best when presented with quantitative aspects of flood management, flood resilience thrives in the more qualitative aspects [16,35], which are also important to consider [59].

Flood risk management is also not especially suited for managing the way in which an affected area recovers from an event. Consider that two events which have the same expected value of damage, may not follow the same timeline for recovery of that damage. Consider, further, that a wealthy urban center may have a higher flood risk than a poorer urban center due to the value of assets involved, though the poorer urban center may have a longer and more difficult recovery process than the wealthier urban center when presented with the same magnitude flooding event.

This demonstrates another distinction of flood resilience from flood risk management. One of the primary objectives of resilience (in almost every definition of the term) is to improve the recovery following an event. So, flood risk management may provide an excellent tool for accountability and reduction of damages, but flood resilience can aid in the reduction of losses (quantitative and qualitative) in the aftermath of an event. The remainder of this work is dedicated to presenting the current state of the literature regarding flood resilience.

3. Flood resilience

In order to organize current flood resilience literature, the following has been grouped around three thematic areas: conceptualizing resilience, measuring resilience and implementing resilience. The section on conceptualizing resilience primarily focuses on defining the term, as this is highly important for guiding the other aspects of application. The section focused on measuring resilience reviews methods of assessing current system resilience and the areas in which resilience can be improved. Finally, the section on implementing resilience discusses current strategies for bringing resilience theory into practice. These three areas are key to understanding what resilience means and how it can be applied to flood management.

3.1. *Conceptualizing resilience*

Throughout the literature, much work is dedicated to defining resilience as a concept for use in flood management [2,40,49,51]. One could argue that the amount of emphasis placed on the nuances of developing a comprehensive definition pales in comparison to the vast need for research into other potentially more applicable aspects of resilience. It would also seem that after years of integrating the topic into environmental hazard management, that a single, unifying definition would be adopted by the field at this point. However, this is not yet the case, perhaps due to the generally fragmented nature of water management [49]. The debate about what it means to be resilient in regard to floods continues [12].

As a solid definition of the term is, in fact, the cornerstone of the theory, defining it merits review of the potential definitions in order to establish a consensus which further work can build upon. Accomplishing this feat will allow future research to devote less time and resource to the most basic aspects of flood resilience in order to delve deeper into the applications of the concept.

Because much has already been conducted in way of developing a definition, this work will not seek to create a formalization of its own for conceptualizing resilience. Rather, some of the most relevant points will be explained in brief, their criticisms summarized and their merits highlighted. Few literature reviews on the topic of resilience begin without mentioning the term’s origin with Holling [33] (a point which is disputed [2]). Though the root of the term holds importance, it is the focus of this work to define resilience in its current application in order to progress the subject forward.

Four main types of definitions are considered here: engineering resilience, ecological resilience, social-ecological resilience and definitions from field applications (often including terms related to both of the former concepts, but not explicitly associated to either). The scope is narrowed in this way because the literature has tended to consider these conceptualizations most relevant. For example, Rodina [49] identified that of 149 articles focused on resilience in water management between 1982 and 2017, 45.6% utilized an engineering resilience definition, 18.8% used a social-ecological resilience definition, 11.4% used an ecological resilience definition and 12.1% used an unspecified resilience definition (the highest ranking categories). In this work, inductive resilience definitions are considered in lieu of unspecified resilience definitions because of the large number and potential issues with categorization. Fischer [23] suggests that there may be more than seventy such resilience definitions in recent literature. Centering the focus to the most applicable definitions will help to move the debate forward by excluding more peripheral definitions of the term.

3.1.1. *Resilience in practice: inductive definitions*

Many conceptualizations of resilience have been constructed as working definitions for practical applications. This type of definition often contains more expanded ideas and utilizes more concrete terms than the more abstract concepts contained in engineering or social-ecological resilience. Because working definitions are created specific to their application, they are numerous and vary widely. However, many utilize similar terminology. Bahadur and Pichon [5] identify some of the key components common to popular working definitions along with the frequency in which they appear among the definitions surveyed (Table 1).

Among the definitions assessed were those used by Action Research for Community Action in Bangladesh (ARCAB), Mercy Corps, International Federation of the Red Cross and Red Crescent Societies (IFRC), the U.S. Agency for International Development (USAID), the UN Development Program (UNDP), Community-Based Resilience Analysis (CoBRA) and the FAO’s Resilience Index Measurement and Analysis (RIMA). Though subtleties exist between the specific terms used, five

Table 1
Components of resilience, their related terms and the frequency in which each term appears in popular working definitions [5].

Component	Description or Related Terms	Frequency
System	The unit or entity that needs to be made resilient. Can be ambiguous term (system, unit) or explicitly identified (household, community, city, ecosystem, country).	(not assessed)
Disturbances	Shocks or stresses affecting system. Ambiguous or explicitly stated (as with system)	(not assessed)
Pre-Event Action	● Anticipate, plan, prepare	4
	● Reduce or manage risk	4
	● Avoid	1
Damage Limitation	● Bounce back, recovery	11
	● Accommodate, absorb, cope	11
	● Minimize loss or cost	4
	● Survive, persist, maintain	3
Managing Change	● Adapt, evolve	10
	● Transform	5
	● Learn	3
	● Reorganize	2

general components were most common: system, disturbance, pre-event action, damage limitation and managing change. The existence of common components demonstrates an opportunity for developing consensus on a resilience definition.

Another working definition not considered in the previous list is that presented by the Intergovernmental Panel on Climate Change, which defines resilience as "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions [34]." This definition incorporates all of the five common components identified by Bahadur and Pichon [5]. Most importantly though, this definition was formed from an international collaboration by a prominent organization. This point may significantly aid in forming needed consensus.

3.1.2. Engineering resilience for complicated systems

Resilience as utilized in engineering systems can be defined as resisting change from an original state while a stress is applied and returning back to that original state after the stress subsides, regaining previous functionality and equilibrium [19,40,49]. This is often referred to as "bouncing back" [19]. Fig. 2 demonstrates the concept.

In the engineering resilience concept, the target goal for the system is to remain at the idealized state. When a disturbance occurs, it is expected that recovery work is oriented at returning the system back to its previous state. It is argued that this approach is one which only maintains the status-quo and lacks the critical component of adaptation. Without adaptation, the city will not learn to better manage such shocks and remains potentially vulnerable to disaster should another disturbance occur [34,36,40,45].

Liao [40] points out that as engineered systems often possess an idealized state in which they are designed to function, this definition has many suitable applications in closed boundary problems. However, the concept fails to adequately describe those systems which are complex or open. The reason is that the disturbance will have changed the system so that the status it falls back to is either no longer possible or has other implications.

It is worth noting, complex refers to a system in which a change of one component can have unforeseen consequences for the whole system — contrary to complicated systems, where an intervention can be reversed or restored. Complicated systems are foremost focused on elements themselves, complex systems consist of situational and changing relations between the elements of the system [10].

Engineering resilience is thus suitable for individual measures of flood protection – a dike, a dam, a mobile barrier, but also the ability of constructions such as bridges or waterways in rivers to withstand the impact of floods. However, flood risk management can better be conceived as a complex system – not only because of the larger spatial scope (i.e. a catchment), but also because of the socio-economic dynamics related to a risk-approach. The levee effect, for example, illustrates that improving flood protection can lead to unintended incentives to accumulate assets behind dikes [6,7,29]. Similarly, flood insurances can set false incentives that change the conditions of a system [11]. In other words, whereas engineering resilience is suitable for flood protection, it falls short on flood risk management.

3.1.3. Ecological and social-ecological resilience for complex systems

Ecological resilience describes how complex systems continue functioning after experiencing a disturbance, namely by the ability to change the state of the equilibrium [8,19,40,49,62]. Like in engineering resilience, ecological resilience describes how systems "absorb shocks" [19,33]. Fig. 3 illustrates the functioning of ecological resilience.

As the system experiences a stress, it initially functions much like the engineering model of resilience in that it resists a state change. If the applied stress or shock is small, the system is likely to return to its initial functional state after a period of time, like in engineering resilience. However, in complex systems, the shock (i.e. a flooding event) changes the system in itself. It may disturb land markets or change people's perception on risk. Respectively, the system reacts in unforeseen ways, such as policy interventions, subsidies, etc. For example, the flood event in 1993 and 1995 at the river Rhine triggered a change in paradigms by initiating a debate on "space for the rivers" [28]. Ultimately, this changed the whole system of flood protection to flood risk management with huge spatial implications – polders have been built, restrictions for building in floodplains have been increased, etc.

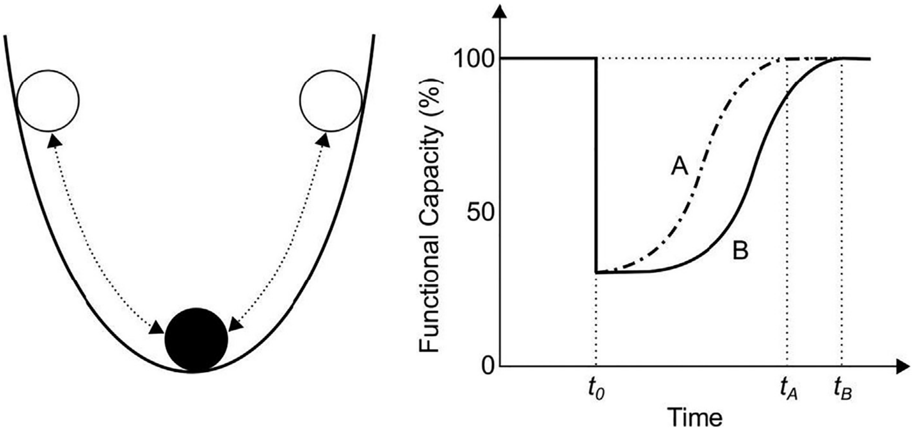

Fig. 2. Model demonstrating the functioning of the engineering resilience definition from Liao [40]. The image on the left demonstrates how this definition focuses on resisting change and returning to an original equilibrium state. Right, shows system functionality over time given an acute disturbance at time t_0. Trajectory A is that of a more resilient system compared with trajectory B, as less time is required to return to 100% functionality.

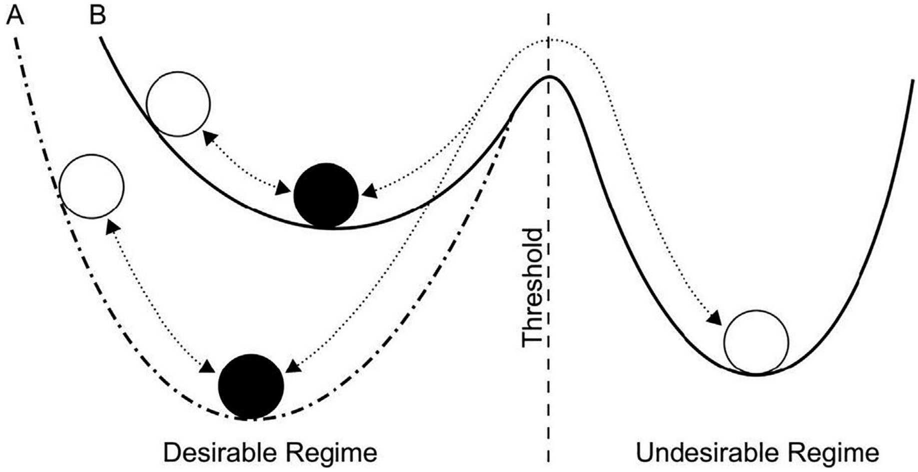

Fig. 3. Model demonstrating the ecological resilience definition from Liao [40]. Initially, the system behaves much like the engineering resilience definition, until a certain disturbance threshold is reached and the system is pushed into a new equilibrium state. Line A demonstrates a more resilient system than line B, which is more easily forced past the threshold and into an undesirable regime.

Similarly, social-ecological resilience (also known as evolutionary resilience [20]) can be defined as the ability of a system to adjust accordingly in order to maintain functionality when it experiences a disturbance [8,49]. This definition is characterized by the ideas of “coping”, “transformation” [49] and “bouncing forward” [19] and does not involve equilibrium states, but rather constant change [20]. When a community experiences an extreme flooding event, it is unlikely to seek to return to the exact state of conditions which existed prior to the event. Instead, communities often seek to make adaptations which improve conditions and help to prevent the extenuating circumstances which were caused by the flood from happening again. This conceptualization incorporates the idea that communities are in a constant state of change, even without disturbances.

These definitions, with their basis in natural systems, better describe the nature of human societies than their engineering counterpart due the incorporation of adaptation. Adaptation is important for making adjustments after flooding events to better prepare for future floods, as pointed out when discussing the engineering resilience definition.

Academic literature supports the ecologically based interpretations as being the most appropriate for use in flood risk management because of the complexities associated with human systems [13,52,54,58]. Liao [40] advocates very strongly for the adoption of ecological resilience as the basis for a flood resilience application primarily due to its higher applicability for a dynamic world. In assessing literature trends, Rodina [49] identified that definitions of resilience in the water management field are beginning to converge around the ecological and social-ecological interpretations, possibly due to an expanded understanding of complexity in the sector which is outgrowing the simplified engineering definition.

3.1.4. Conceptual model

Though not an explicit definition, a conceptual model (originally developed by Community and Regional Resilience Institute [17] and further adapted by White et al. [60] and Dabson [19]) representing resilience is shown in Fig. 4. This model possesses many attributes which are overlooked in other similar models, while combining attributes of engineering and social-ecological resilience. For instance, functional capacity (vertical axis) is not bound by a maximum. This is characteristic of societies because they are continuously developing and do not, therefore, possess an idealized maximum-capacity state. The model incorporates the immediate, added benefit of incorporating resilience measures for societal and economic gains. Additionally, this model provides for multiple outcomes (Lines A, B, C and D), each of which represent new, post-shock equilibrium states.

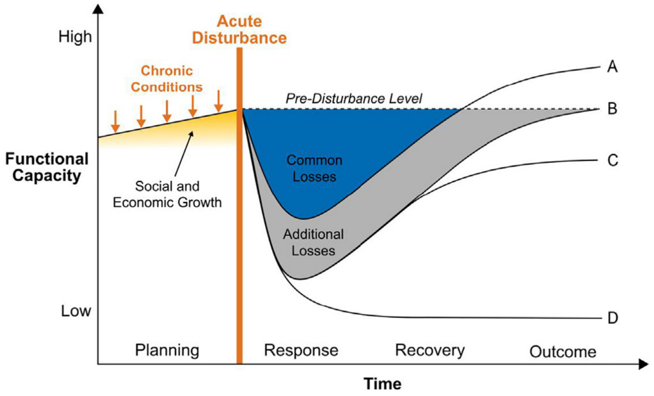

Fig. 4. A well-developed model of resilience which incorporates an unbounded functional capacity axis, social and economic gains from implementing resilience and multiple pathways following a disturbance (including a pathway for adaption and improvement, Path A) [17,19,60].

3.2. Measuring resilience

Measurement of resilience is among the most applicable and important aspects of resilience. Without sound resilience measurement practices, it is difficult or impossible to adequately determine how prepared a community is to face a flooding event. It is similarly difficult to determine which interventions should be made and to what extent those interventions will improve resilience. This directly hinders the ability of managers to make informed decisions and to produce an accountability of investments in resilience measures.

Consensus on the topic of resilience measurement is relatively weak. This is likely due to the difficulty of standardizing approaches to resilience which are often highly localized and strongly varying. Dabson [19] summarizes the current situation: “The challenge is to develop a measurement system that is comprehensive across physical, economic, and social dimensions, incorporates rigorous procedures for data collection, analysis, weighting, and combination, and is open and transparent.” It is clear that a unified approach to applying resilience in flood management is challenging, though not impossible if research efforts focus their attention on clarifying the issues of scale and process.

3.2.1. Resilience indicators

Because resilience measurement must incorporate so many vastly different dimensions, the first question becomes: which aspects of resilience can be measured? There is debate among some in the field about whether vulnerability or resilience can be directly measured at all [41,63]. Therefore, as a potential solution to this dilemma, indicators

Table 2
Classifications of resilience indicators and their corresponding descriptions, adapted from Lisa, Schipper, and Langston [41] and OECD [47].

Indicator Type	Description
System Resilience (Outcome)	Indicators which provide insight on the resilience of the main components of the system over time, including how the overall well-being of people and the system is affected when shocks actually occur. For example, how social capital is affected by an extreme flooding event. These indicators should be complemented by negative resilience indicators.
Negative Resilience	Indicators which monitor whether people are using strategies to boost resilience that may have negative impacts on other areas of the system. For example, neglecting one people group to ensure the resilience of another.
Process	Indicators which ensure that the resilience road map is being used in policy making and programming. For example, amount of funds secured for activities supporting resilience.
Output	Indicators which show the results of implementing different parts of the resilience road map. For example, number of volunteers trained for emergency response.
Proxy Impact	Indicators which allow for indirect estimation of resilience aspects which are not easily or reasonably measured directly. These must be used with caution, but can be necessary when other more nuanced measures (such as system resilience indicators) are difficult to create, or difficult to communicate to a specific target audience. For example, the use of water depth as an indicator of recovery time following a flood.

have emerged as the most promising method for assessment. But there are many challenges to consider for indicator development and use.

OECD [47] categorizes indicators into five groups according to the aspects of resilience which each attempts to measure. These include: system resilience indicators, negative resilience indicators, process indicators, output indicators and proxy impact indicators. Table 2 describes each of these in detail.

Likely the most well-known indicators in use today are those developed by Arup and the Rockefeller Foundation through their work titled City Resilience Index [3]. There are 52 indicators used in the metric. The indicators are divided into four dimensions, which are subsequently subdivided into three goals per dimension (twelve goals total).

The four dimensions used in the index cover aspects of community like *Health and Well-being*, *Economy and Society*, *Infrastructures and Ecosystems* and *Leadership and Strategy*. Fig. 5 displays the *Infrastructures and Ecosystems* dimension as an example of the City Resilience Index structure.

3.2.2. *Resilience indices*

Indices are metrics used to visually convey the status of resilience in a system at the time of measurement. Indicators are used to quantify various aspects which directly or indirectly relate to the system's resilience within a particular theme. These metrics are often presented in graphical form, so to be easily communicated to stakeholders, like the public and to policy makers.

The fully developed version of Arup's City Resilience Index [3] discussed in the previous subsection is an typical example of what is commonly used. Consider the seven inner rings in Fig. 6. They correspond to the qualitative attributes *Flexible*, *Redundant*, *Robust*,

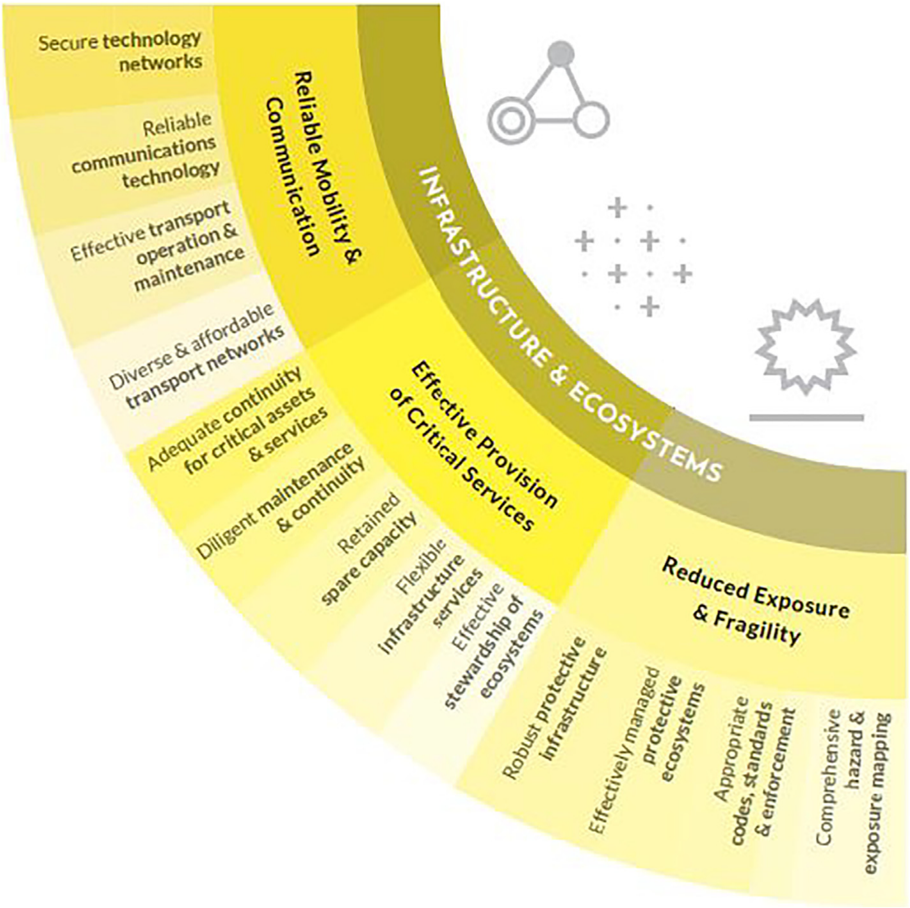

Fig. 5. The Infrastructure and Ecosystems dimension of the City Resilience Index [3] and its corresponding goals and indicators.

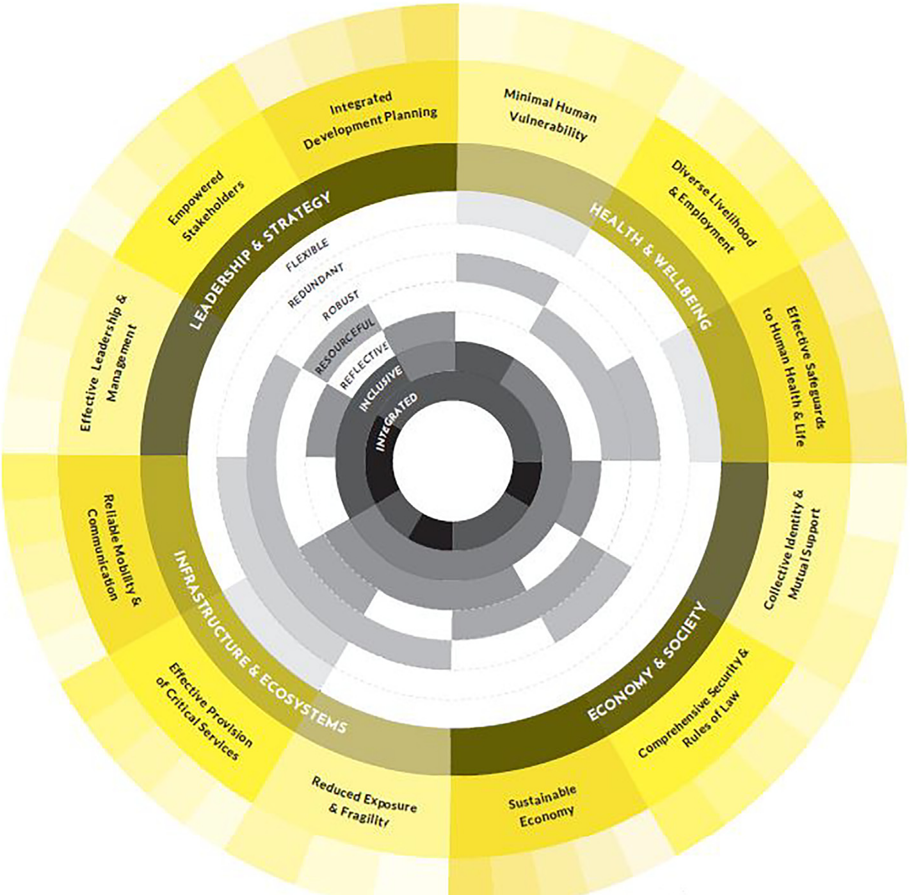

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Fig. 6. An example of the City Resilience Index [3] with filled inner rings which assess performance. The darkest color represents "very poor" and lightest color represents "excellent."

Resourceful, *Reflective*, *Inclusive* and *Integrated*.

Scores are generated as the indicators are measured via qualitative and quantitative assessment. The places on the inner rings then get a color code corresponding to the outcome (darkest color represents "very poor" and lightest represents "excellent"). The resulting product is often primarily visual. Messages are conveyed in a way that are easily understood by most, regardless of background or education. For cross-sector collaboration and education of the public, this is quite important. The drawback of such comprehensive methods is that data is often not equally available across different areas [53]. The resulting indices of computed resilience are therefore not directly comparable across different studies. The helpfulness of this method of communicating resilience for flood management is to be determined.

3.3. Implementing resilience

The definition that resilience describes the ability of a system to absorb shocks becomes imprecise when applied to specific situations. The questions that arise are: (i) what are the system boundaries, (ii) what exactly does absorb mean and (iii) what is a shock event? Meerow, Newell, and Stults [42] add to the definition that this ability relates to the socio-economic and socio-technical networks across temporal and spatial scales. This indicates that not only the disciplinary perspective, but also time and spatial scale matter. The following sections discuss each of these points.

3.3.1. Time matters

On a theoretical notion, resilience describes the ability of a system to absorb shocks. Especially quantitative scientists and engineers often prefer more narrowed-down resilience concepts; for instance, in water resource management focusing on time elapsed [21,31]. This shows that the definition and the boundaries of the system are crucial to understand what resilience means. So the question of the time frame applied to resilience is important to decide whether a system is resilient or not.

Forrest et al. [24] defines resilience through the actions taken during three phases of the flood management timeline. The first is the pre-flood phase which includes the actions taken to mitigate and prepare for floods. The second phase is the during-flood phase comprising resistance of and response to the flood at the time it is occurring. The last phase is the post-flood phase and includes recovery and adaptation after a flood.

Similarly, Davoudi et al. [20] mentions the importance of considering the panarchy model of adaptive cycle. This cycle describes the pattern by which resilience evolves over time. The four phases of the cycle represent the stages in which communities find themselves as they deal with increasing and decreasing resilience following flooding events. The phases include: conservation phase (stable and inflexible period of slower growth and low resilience), creative destruction phase (period of uncertainty at the time of a flooding event), reorganization phase (highly dynamic and highly resilient period of innovation) and growth phase (period of rapid growth and decreasing resilience). According to this model, it is the flooding event which produces resilience in a community by forcing change.

3.3.2. Scale matters

Among the most important attributes for defining systems is to establish the spatial extent of that system. Spatial scale in human systems

Table 3
Terms used to describe spatial scale in 174 recent articles on resilience and their frequency of occurrence, identified by Cai et al. [14].

Spatial Scale	Number of Papers	Percentage (%)
Community	28	16.1
Individual/Household	17	9.8
County	15	8.6
City	13	7.5
Facility	9	5.2
Block Group	5	2.9
State/Province	4	2.3
Others	32	18.4
Not Specified	51	29.3

can, however, be difficult to define. Perhaps this is why there exists such little uniformity among the vocabulary used to describe spatial scale in flood resilience. Table 3 lists some of the various terms used to express the spatial scale in recent flood resilience literature (if it is explicitly stated at all), as identified by Cai et al. [14].

Nonetheless, it is important for those applying or measuring resilience to clearly define the spatial scale considered, as the idea of what makes a system resilient can vary greatly across scale. For example, an individual construction can be resilient if it is able to withstand and absorb a shock event, but also a society as a whole can be resilient if it is able to financially recover from a shock event.

3.3.3. Disciplines matter

It is stressed in literature that resilience also has a non-structural dimension in policy and practice [50]. We can distinguish resilience in terms of civil engineering, financial resilience, economic resilience etc. For that matter, a good example is that an insurance coverage of a system can contribute to resilience of the whole system; from an engineering perspective constructions and buildings have been destroyed and could not be considered resilient. An example is the destruction of a railway track during a flood event in Eastern Germany. In this case, the track was destroyed and the Rover company reconstructed their track at the same place in the same way. Asked about resilience, the company said that it would be cheaper to reconstruct the rail track after every flood event than the effort to try to relocate the track to an alternative route, because that would raise issues like property rights and planning issues. This is an example of a financial resilience that contradicts a resilience from a civil engineering point of perspective. This means that measuring resilience also implies making some thoughts about the disciplinary perspectives through which resilience is viewed.

So finally, resilience depends on the spatial and temporal scale and also the disciplinary perspective. Which perspective is most appropriate for a certain system or a certain situation depends on a careful balancing of all involved stakeholders. That means that resilience is highly locational and context specific. In other words, resilience is a political concept.

4. Conclusions

Flood risk and flood resilience both have much to offer in the management of floods. Each presents its own benefits and challenges. Resilience, for example, offers a more integrated approach to the problem of managing floods by measuring and strengthening the less tangible aspects of community. This, however, comes at the expense of sometimes complicated metrics plagued by individualized approaches and a general lack of comparability across regions.

Flood risk management, on the other hand, provides a clear metric with common units which can be readily compared and used to derive accountable interventions. Flood risk management's central focus on the immediate impacts of floods and its inability to adequately consider recovery are among the approach's shortcomings. Therefore, it is not an abandonment of risk management practices and full adoption of resilience strategies which will produce cities ready for future flooding hazards. Nor is a continuation of risk based management alone adequate to handle future needs. Rather, it is a complementary posture in which the strengths of each strategy inform the practice of the other.

By combining flood resilience and flood risk, measures can be effective against a broader range of hazards than when considering either method alone. This approach helps to address some of the uncertainties involved with flood risk management, not by reducing them, but by adding much needed flexibility to a field oriented toward optimization considering social and economic pathways.

As presented, the current strategies attempting to bridge risk and resilience are lacking. They are often little more than a peripheral application of flood resilience, while focusing primarily on flood risk management. This falls well short of reaching the potential benefits of a truly combined approach.

The pace of bringing this complementary structure into practice will need to match the urgency associated with climate change adaptation. However, it is unlikely that the currently fragmented development of flood resilience metrics and strategies will create a unified implementation in that required time frame. A path forward will be more likely found when more research is dedicated to studying applications and less upon deriving new resilience frameworks. Instead of development of new metrics for each new community or region studied, there is a need for research on applications of existing metrics to multiple study areas in order to discern which aspects are most promising. Modification of metrics for individual studies will remain inevitable due to the nature of the subject. However, the temptation to add new metrics to the literature does little to build the much needed consensus around resilience theory.

There is much work still remaining to be done for the future of resilience. Upon reviewing the literature, it became obvious that there currently exists little research making systematic comparisons of resilience frameworks and indicators. This is likely due to the difficultly of such an undertaking as both vary widely in approach and scope.

It may also be due to the fact that most of the work in regard to development of resilience frameworks and indicators is currently being conducted primarily by individual policy research institutes, governmental bodies and non-governmental organizations. It appears that each group tends to frame their approach on the specific characteristics of the regions which each supports and develops its frameworks in a similarly context-specific manner.

A categorical review of resilience frameworks and indicators which forms groups according to type and area focus, assesses the thematic areas of interest, and which evaluates implementation case studies of each would be a highly useful resource. Though similar small scale studies have been conducted, a more in-depth survey would help to better understand the current state of resilience work and help to forge a more unified path forward.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasec.2020.100059.

References

[1] J.C.J.H. Aerts, et al., Integrating human behaviour dynamics into flood disaster risk assessment, Nat. Clim. Chang. 8 (2018) 193–199, https://doi.org/10.1038/s41558-018-0085-1.
[2] D. Alexander, Resilience and disaster risk reduction: an etymological journey, Nat. Hazards Earth Syst. Sci. 13 (2013) 2707–2716, https://doi.org/10.5194/nhess-13-2707-2013.
[3] Arup and the Rockefeller Foundation. City Resilience Index Brochure. 2018. URL: https://www.cityresilienceindex.org/#/resources (visited on 08/2019).
[4] Ashley, R. et al. Frameworks for adapting to flood risk: experiences from the EU's flood resilient city project. In: Proceedings of the 1st IAHR European Congress, Sheffield, UK (2010).

[5] A. Bahadur, F. Pichon, Analysis of Resilience Measurement Frameworks and Approaches. Technical Report. London, UK: Overseas Development Institute, 2017. doi: 10.13140/RG.2.2.13892.94082.

[6] G. di Baldassarre, et al., Debates – perspectives on socio-hydrology: capturing feedbacks between physical and social processes, Water Resour. Res. 51 (2015) 4770–4781, https://doi.org/10.1002/2014WR016416.

[7] G. di Baldassarre, et al. Hess Opinions: An interdisciplinary research agenda to explore the unintended consequences of structural flood protection. In: Hydrol. Earth Syst. Sci. Discuss. 1–11 (2018). doi: 10.5194/hess-2018-333.

[8] R. Bhamra, S. Dani, K. Burnard, Resilience: the concept, a literature review and future directions, Int. J. Prod. Res. 49 (18) (2011) 5375–5393, https://doi.org/10.1080/00207543.2011.563826.

[10] L. Boelens, G. de Roo, Planning of undefined becoming: First encounters of planners beyond the plan, Planning Theory 15 (1) (2016) 42–67, https://doi.org/10.1177/1473095214542631.

[11] W. Botzen, Property rights for insurance markets to enable adaptation to natural disaster risks, in: Routledge complex real property rights series. Property rights and climate change: Land-use under changing environmental conditions. Ed. by F. van Straalen. Ed. by T. Hartmann. Ed. by J. Sheehan. New York: Routledge, 2018, pp. 165–181.

[12] K.M. de Bruijn, Resilience and flood risk management, Water Policy 6 (2004) 53–66, https://doi.org/10.2166/wp.2004.0004.

[13] K. M. de Bruijn, Resilience and flood risk management: a systems approach applied to lowland rivers. Delft: Delft University Press, 2005.

[14] H. Cai, et al., A synthesis of disaster resilience measurement methods and indices, Int. J. Disaster Risk Reduct. 31 (2018) 844–855, https://doi.org/10.1016/j.ijdrr.2018.07.015.

[16] K. Chen, J. Leandro, A Conceptual Time-Varying Flood Resilience Index for Urban Areas : Munich City. In: Water 11, 830 (2019). doi: 10.3390/w11040830.

[17] Community and Regional Resilience Institute. Resilient Communities, Resilient Regions, A Resilient Nation. Washington, D.C.: DHS University Summit, 2008.

[18] S.L. Cutter, et al., A place-based model for understanding community resilience to natural disasters, Global Environ. Change 18 (2008) 598–606, https://doi.org/10.1016/j.gloenvcha.2008.07.013.

[19] B. Dabson, Planning for a More Resilient Future. A Guide to Regional Approaches. Technical Report. National Association of Development Organizations (NADO) Research Foundation, 2015. doi: 10.13140/RG.2.1.2434.2480.

[20] S. Davoudi, et al. Resilience: A Bridging Concept or a Dead End? (2012) doi: 10.1080/14649357.2012.677124.

[21] L. Duckstein, E.J. Plate, Engineering Reliability and Risk in Water Resources. location: Springer (NATO ASI Series, Series E, 124), 1987. doi: 10.1007/978-94-009-3577-8.

[22] European Commission. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. Official Journal of the European Union. 2007.

[23] Fischer, L. More than 70 ways to show resilience. In: Nature 518, 35 (2015). doi: 10.1038/518035a.

[24] S. Forrest, E.M. Trell, J. Woltjer, Civil society contributions to local level flood resilience: before, during and after the 2015 Boxing Day floods in the Upper Calder Valley, In: Trans. Inst. Br. Geogr. 44 (2019), pp. 422–436. doi: 10.1111/tran.12279.

[25] R. de Graaf, N. van de Giesen, F. van de Ven, Alternative water management options to reduce vulnerability for climate change in the Netherlands, Natural Hazards 51 (2009) 407–422, https://doi.org/10.1007/s11069-007-9184-4.

[26] U. Grünewald, Vom Hochwasser-'Schutzversprechen' zum 'Hochwasser-Risikomanagement', in: Hochwassermanagement. Ed. by R. Jüpner. Aachen: Shaker, 2005, pp. 5–22.

[28] T. Hartmann, Land Policy for German Rivers: Making Space for the Rivers. In: Making Space for the River: Governance Experiences with Multifunctional River Planning in the US and Europe. Ed. by J. F. Warner, A. van Buuren, and J. Edelenbos. London: IWA Publishing, 2012, pp. 121–133.

[29] T. Hartmann, R. Jüpner, Editorial: The flood risk management plan between spatial planning and water engineering, in: Journal of Flood Risk Management, Virtual Special Issue (2014).

[30] T. Hartmann, R. Jüpner, The Flood Risk Management Plan – an essential step towards the institutionalization of a paradigm shift, Int. J. Water Governance 2 (2) (2014) 107–118, https://doi.org/10.7564/13-IJWG5.

[31] T. Hashimoto, J.R. Stedinger, D.P. Loucks, Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation, Water Resour. Res. 18 (1) (1982) 14–20, https://doi.org/10.1029/WR018i001p00014.

[32] D.L.T. Hegger, et al., Toward more flood resilience: Is a diversification of flood risk management strategies the way forward?, in: Ecology and Society (2016). doi: 10.5751/ES-08854- 210452.

[33] C.S. Holling, Resilience and sustainability of ecological systems, Annu. Rev. Ecol. Syst. 4 (1973) 1–23, https://doi.org/10.1146/annurev.es.04.110173.000245.

[34] IPCC. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change. Cambridge, England: Cambridge University Press, 2012. doi: 10.1136/jech-2012-201045.

[35] A. Keating, et al. Development and testing of a community flood resilience measurement tool, in: Nat. Hazards Earth Syst. Sci. (2017), pp. 77–101. doi: 10.5194/nhess-17-77-2017.

[36] R.J.T. Klein, R.J. Nicholls, F. Thomalla, Resilience to natural hazards: how useful is this concept? Global Environ. Change Part B: Environ. Hazards 5 (1) (2003) 35–45, https://doi.org/10.1016/j.hazards.2004.02.001.

[37] F. Klijn, et al., Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation, in: Mitigation and Adaptation Strategies for Global Change 20 (6 2015), pp. 845–864. doi: 10.1007/s11027-015-9638-z.

[38] C. Kuhlicke, Risk and resilience in the management and governance of natural hazards, in: Oxford Research Encyclopedia of Natural Hazard Science (2019). doi: 10.1093/acrefore/ 9780199389407.013.299.

[39] S. Lhomme, et al., Analyzing resilience of urban networks: a preliminary step towards more flood resilient cities, Nat. Hazards Earth Syst. Sci. 13 (2013) 221–230, https://doi.org/10.5194/nhess-13-221-2013.

[40] K.-H. Liao, A theory on urban resilience to floods—a basis for alternative planning practices, in: Ecology and Society 17.4 (2012). doi: 10.5751/ES-05231-170448.

[41] E. Lisa, F. Schipper, L. Langston, A comparative overview of resilience measurement frameworks: analysing indicators and approaches. Overseas Development Institute, 2015.

[42] S. Meerow, J.P. Newell, M. Stults, Defining urban resilience: a review, Landscape Urban Plann. 147 (2016) 38–49, https://doi.org/10.1016/j.landurbplan.2015.11.011.

[43] B. Merz, et al., Fluvial flood risk management in a changing world, Nat. Hazards Earth Syst. Sci. 10 (2010) 509–727, https://doi.org/10.5194/nhess-10-509-2010.

[44] P.C.D. Milly, et al., Stationarity is dead: whither water management? Science 319 (5863) (2008) 573–574, https://doi.org/10.1126/science.1151915.

[45] T. Mitchell, K. Harris, Resilience: A Risk Management Approach. Technical Report. Over- seas Development Institute, 2012.

[46] A. Morrison, C.J. Westbrook, B.F. Noble, A review of the flood risk management governance and resilience literature, Flood Risk Manage. 11 (2018) 291–304, https://doi.org/10.1111/jfr3.12315.

[47] OECD. Guidelines for Resilience Systems Analysis. OECD Publishing, 2014.

[48] H. Patt, R. Jüpner, Hochwasser Handbuch: Auswirkungen und Schutz. Heidelberg: Springer, 2013.

[49] L. Rodina, Defining "water resilience": debates, concepts, approaches and gaps, in: Wiley Interdisciplinary Reviews: Water 6.2 (2018). doi: 10.1002/wat2.1334.

[50] B.R. Rosenzweig, et al., Pluvial flood risk and opportunities for resilience. In: WIREs Water 5.6 (2018). doi: 10.1002/wat2.1302.

[51] J. Schanze, ed. Resilience in flood risk management – exploring its added value for science and practice. FLOODrisk 2016 – 3rd European Conference on Flood Risk Management. Vol. 7.08003. E3S Web of Conferences, 2016. doi: 10.1051/e3sconf/20160708003.

[52] M. Schlüter, C. Pahl-Wostl, Mechanisms of resilience in common-pool resource management systems: an agent-based model of water use in a river basin, in: Ecology and Society 12.4 (2 2007). doi: 10.5751/ES-02069-120204.

[53] J.K. Summers, et al., Measuring community resilience to natural hazards: the natural hazard resilience screening index (NaHRSI)-development and application to the United States, GeoHealth 2 (12) (2018) 372–394, https://doi.org/10.1029/2018gh000160.

[54] B. Tempels, T. Hartmann, A co-evolving frontier between land and water: dilemmas of flexibility versus robustness in flood risk management, In: Water International 39 (6 2014), pp. 872–883. doi: 10.1080/02508060.2014.958797.

[55] J. Twigg, Characteristics of a Disaster-Resilient Community. Second Edition. University College London, 2009.

[56] C. Twigger-Ross, et al. Flood Resilience Community Pathfinder Evaluation. Rapid Evidence Assessment. London: Department for Environment, Food and Rural Affairs, 2014.

[57] United Nations Office for Disaster Risk Reduction. Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction. A/71/644. United Nations General Assembly, 2016.

[58] M. Vis, et al., Resilience strategies for flood risk management in the Netherlands, Int. J. River Basin Manage. 1 (1) (2003) 33–40, https://doi.org/10.1080/15715124.2003.9635190.

[59] Z. Vojinovic, et al., Holistic approach to flood risk assessment in areas with cultural heritage: a practical application in Ayutthaya, Thailand, Nat. Hazards 81 (1) (2016) 589–616, https://doi.org/10.1007/s11069-015-2098-7.

[60] R.K. White, et al., A practical approach to building resilience in America's communities, Am. Behav. Scientist 59 (2) (2015) 200–219, https://doi.org/10.1177/0002764214550296.

[61] I. White, et al., Flood resilience technology in Europe: identifying barriers and co-producing best practice, J. Flood Risk Manage. (2016), https://doi.org/10.1111/jfr3.12239.

[62] T.H.F. Wong, R.R. Brown, The water sensitive city: principles for practice, Water Sci. Technol. 60 (3) (2009) 673–682, https://doi.org/10.2166/wst.2009.436.

[63] J. Hinkel, Indicators of vulnerability and adaptive capacity: Towards a clarification of the science-policy interface, Global Environ Chang. 21 (2011) 198–208, https://doi.org/10.1016/j.gloenvcha.2010.08.002.