Flood resilience

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Flood resilience: a systematic review

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Hydro-hazards are increasing in frequency due to climate change which has inspired a cultural change in Flood Risk Management (FRM). Uncertainty associated with climate change has resulted in a shift towards flood resilience as it helps deal with unexpected climatic perturbations that impact extreme flows. The concept of resilience has increased in popularity, leading to a multitude of definitions, measurements and applications. This paper systematically reviews the FRM literature to provide clarity on the differing perspectives of resilience and how they influence successful implementation of the concept. Our analysis assesses where FRM is positioned within three pre-defined interdisciplinary understandings of resilience. The polysemic nature of resilience has produced a multitude of different perspectives that prevent successful operationalisation. Resilience is interdisciplinary; therefore it requires integration between top-down and bottom-up FRM approaches, as well as a more holistic approach to the interdependence between temporal and spatial scales.

Keywords: flood risk management; resilience; systems approach

1. Introduction

According to the latest United Nations urbanisation projections, 55% of the global population reside in urban areas in 2018, displaying a 24% increase from 1950 – furthermore, the rate of urbanisation is set to increase in the future, such that 68% of the world’s population are expected to be urban by 2050 (United Nations 2018). The increased agglomeration of people, buildings and infrastructure suggest a more vulnerable society in the event of climate-induced hydro-hazards (Jahn 2015).

A stressed hydrological cycle as a result of climate change has led to an increase in the frequency of natural hazards, such as floods, in recent years (Ghazali \textit{et al.} 2018). Events such as the 2007 UK floods saw around 48,000 households and 7,300 businesses flooded, as well as 13 deaths (Cabinet Office 2008), highlighting the devastating impacts of extreme events. Recent research predicts that North-western European cities and those on the British Isles can expect a 50% increase in their 10-year high flows between 2015 and 2100, subsequently resulting in more frequent
flooding (Guerreiro et al. 2018). Moreover, significant uncertainty within climate change projections presents problems for decision-makers and practitioners on how to deal with the threat of climate change (Reynard et al. 2017). Collet, Beevers, and Prudhomme (2017) and Kundzewicz et al. (2017) have recognised the importance of understanding climate change uncertainty to provide robust projections and limit the unpredictability of extreme flood events. Despite significant efforts to reduce uncertainty, the immediate risk stemming from more frequent, unpredictable hazards and thus more severe consequences, highlights the need for alternative flood risk management strategies (FRM), such as resilience.

The term resilience was at first introduced in the field of ecology by Holling (1973) and has since found popularity in the fields of social science, psychology and disaster management. At a fundamental level, resilience relates to a system's ability to resume functionality in the wake of a perturbation. However, the widespread adoption
of resilience among disciplines has led to ambiguity surrounding definitive application of the concept. To inform the 100 Resilient Cities framework, Martin-Breen and Anderies (2011) reviewed the resilience research to produce a resilience spectrum of increasing complexity based on three interdisciplinary frameworks: Engineering Resilience, Systems Resilience, and Resilience in Complex-Adaptive Systems (Figure 1).

These frameworks align with others in the literature that have different terminology, see for example: engineering resilience, ecological resilience and socio-ecological/revolutionary resilience (Douven et al. 2012). This paper uses Martin-Breen and Anderies (2011) framework as it accounts for over 50 years of interdisciplinary resilience research, therefore providing a robust overview of the concept. The definitions are:

**Engineering resilience**: conceptualised as maintaining the status quo and defined as the ability to withstand a large disturbance without, in the end, changing, disintegrating, or becoming permanently damaged; to return to normal quickly; and to distort less in the face of such stresses (6). Engineering resilience is not reflective of the engineering discipline, but it is a conceptual framework that can be applied to any domain. This framework stresses the ability of a system to bounce-back to a previous state and is associated with the emergency recovery stage of a shock event.

**Systems resilience**: defined as maintaining system function in the event of a disturbance (7). Although systems resilience and engineering resilience are both associated with achieving a state of normality after the event, the main difference is the notion of ‘bounce-forth’ as opposed to ‘bounce-back’. It stresses that a system has interacting parts, which can adopt different states in the event of a disturbance to maintain functionality.

**Complex adaptive systems resilience**: the fundamental difference within this framework is the ability of the system to adapt and transform. Complex adaptive systems is the ability to withstand, recover from, and reorganise in response to crisis (7). This framework acknowledges a systems ability to radically transform to a new state in the wake of a disturbance, and is therefore focused on longer-term resilience.

The application of resilience in FRM is vast. Fisher (2015) finds more than 70 definitions of resilience across the scientific literature. At a time when clear and concise FRM strategies are necessary to protect our systems from the effects of climate change, the inconsistency in which resilience is conceptualised and applied may lead to inadequate FRM as a result. Efforts have been made across Europe to develop multidisciplinary frameworks for flood resilience (e.g., CORFU, FLOODsite, FloodProBE) through research initiatives. Despite reviews of resilience frameworks applicable to broad disaster management and systems engineering (see e.g., Cerè, Rezgui, and Zhao 2017; Hosseini, Barker, and Ramirez-Marquez 2016) there exists no review of the academic literature which systematically explores how the resilience concept is perceived, measured and operationalised in FRM in order to consolidate current understanding.

Therefore, the aim of this systematic review is to provide an understanding of how resilience is perceived in FRM along this interdisciplinary spectrum of resilience, and what this means for operationalising the concept in order for resilience to reach its full potential. To develop this understanding, the following research questions are addressed:

1. What are the most commonly adopted perspectives on resilience throughout FRM?
2. How is resilience assessed within FRM?
3. How do the differing perspectives on resilience influence implementation and operationalisation of the concept?
2. Methodology

In this section, we outline the strategy used to identify the FRM resilience literature. A systematic review differentiates from a conventional review in terms of rigor, repeatability, and completeness (Righi, Saurin, and Wachs 2015). In order to meet this criterion, we ensured the methodology was explicit and reproducible by following clearly stated objectives with a set of pre-defined eligibility criteria, and a systematic search to identify all potential papers (Liberati et al. 2009). The four steps in the literature search are illustrated in Figure 2, outlining the number of papers excluded at each stage.

Our analysis of resilience in FRM was based solely on how academia was employing the term; therefore our database search was restricted to peer reviewed journal articles and conference papers printed in English. Following our research objectives, the three resilience frameworks formed the basis of our search terms in order to assess where FRM currently lies on the resilience spectrum outlined in the review (see Martin-Breen and Anderies 2011). Consequently, our search terms were: Resilien* AND Flood; Resilien* AND “Engineering”; Resilien* AND “Systems”; Resilien* AND “Complex Adaptive Systems.” These terms were searched in both Web of Knowledge and Scopus databases on December 2017, with no lower date set.

After establishing appropriate search terms, pre-defined eligibility criteria were developed, as shown in Table 1. This criteria was piloted on 20 abstracts and adjusted as required. Having the predefined inclusion/exclusion criteria ensured consistent decision making (Shamseer et al. 2015). This criteria was applied by two main authors working independently during the abstract screening stage and cross-checked in order to minimise the potential for bias. This process was repeated at the full text screening stage along with the quality check, leaving a total of 67 papers to be included in the review.

Figure 2. Objective search process for identifying flood resilience.
To explore the spectrum of ways in which resilience is conceived within FRM, all papers were analysed and their aspects noted. A frequency analysis was conducted to determine the most common aspects of resilience, which were then matched to each of the three frameworks of resilience. Although, Martin-Breen and Anderies (2011) imply that complex adaptive systems is a continuation of both engineering and systems frameworks, our methods focus on the unique aspects of each framework to help differentiate where papers lie on the resilience spectrum. In theory, the engineering and systems frameworks emphasise the possibility of returning to a previous state in the short-term, but complex adaptive systems require that short-term recovery is accompanied by a longer-term plan to ensure that the system is in a less vulnerable state in the future. The resilience definition in each paper was matched to the distinct aspects of each framework (Figure 1) in order to identify the commonality and spread across the identified three frameworks. When recovery was cited as an aspect of resilience, the full paper was assessed to determine the temporal scale of application. This aims to provide clarity (or lack thereof) on the utilisation of the resilience concept within FRM.

In order to determine how resilience is measured and applied within FRM, the methods used in each paper were recorded in a classification table and categorised into either qualitative or quantitative approaches. Along with the methodological approach, the spatial scale of analysis was classified into either household scale, community scale, city scale, or national scale. Papers were then further classified as to whether they approached resilience from a technical or social perspective, a combination of both, or a strategic perspective. Technical studies involved a more top-down approach with numerical or engineering methods, whereas social studies approached resilience from a more bottom-up, human-centred perspective. Strategic studies included papers which combined science with long-term policy and decision making. Divergence in methods depending on perspective became more apparent at these different spatial scales, allowing for identification of research gaps as well as highlighting the interdependencies between spatial scales of resilience. This classification also allowed for analysis of the temporal scales associated with the resilience assessment approaches. Emergent themes surrounding the debate on defining resilience were analysed to facilitate understanding of the different choice of frameworks, as well as the trade-offs when operationalising resilience.

We acknowledge the limitations of this review based on the strict search criteria. Only papers which defined what is meant by resilience were included, excluding papers which contribute to resilience without acknowledging it explicitly. Only papers which were printed in English were included, potentially limiting our understanding of how flood resilience is employed in other countries. However, the decision not to limit the geographical scope of the study aims to minimise this bias and gain a unique

| Inclusion criteria                                      | Exclusion criteria                                                                 |
|--------------------------------------------------------|-----------------------------------------------------------------------------------|
| Papers which defined and measured/                     | Papers which do not define resilience                                              |
| applied the resilience concept in the context of FRM    | Papers which only list resilience as a co-benefit of another project               |
|                                                        | Papers which specify the resilience of a particular material/product               |
|                                                        | Papers which focused on coast flooding, sea level rise flooding, or flooding amongst other natural hazards. |
insight into different approaches to resilience in various cultural contexts for a more complete understanding of flood resilience.

3. Results
Results from our initial search strategy found 425 journal articles and conference papers that featured our search terms, which have risen exponentially in the last few years (Figure 3).

3.1. Resilience spectrum
The frequency analysis shows that the most frequently cited aspect of resilience was “recover”, accounting for 49% of the papers within the final database. Either “absorb,” “adapt” or “function” then account for approximately 25% of papers (Figure 4). The frequencies of these aspects suggest that all three resilience frameworks are accounted for to some extent.

However, when the aspects were categorised in accordance with the three frameworks of resilience – Engineering, Systems and Complex Adaptive Systems (Martin-Breen and Anderies 2011) – it becomes evident that the majority of papers fall within the engineering or systems frameworks (Figure 5).

Only 15% of papers within the database consider resilience aspects that account for all three frameworks. This suggests that these papers consider resilience as an ability to prepare for any disturbances pre-event and being able to resist the impacts (Engineering Resilience), cope with the effects and maintain functionality throughout the disturbance (Systems Resilience), and then adapt and learn post-disturbance so as to increase future resilience (Complex Adaptive Systems). However, the majority of papers (55%) only consider engineering, systems or engineering and systems related

![Figure 3. Resilience papers published annually, 1998 – 2017.](image-url)
Figure 4. TagCloud highlighting resilience aspects used in definitions (Numbers next to aspects represent the number of times each aspect was cited across the 56 definitions used in database).

Figure 5. Papers associated with the three resilience frameworks. Asterisk denotes that which state recovery in their definition without differentiating between short or long term recovery. van Ree et al. (2011) have been excluded as their definition only included the recovery aspect with no temporal indication, and therefore could not be situated on the spectrum.
aspects of resilience within adopted definitions, thus indicating that a number of papers do not consider resilience to be an iterative, adaptive process. Moreover, 9% of papers account for both engineering and complex adaptive systems frameworks, highlighting an omission of systems resilience aspects within resilience definitions.

3.1.1. Perceptions of flood resilience

A dichotomous approach to resilience has sparked debate across the literature. Within this systematic review, this has been conceptualised as either resistance vs resilience (e.g., Hammond et al. 2015; Restemeyer, Woltjer, and van den Brink 2015; Hegger et al. 2016); reactive or proactive (e.g., Orr et al. 2016); flood control vs flood adaptation (e.g., Liao 2014); robustness vs. flexibility (Tempels and Hartmann 2014); structural vs. functional (e.g. Mugume et al. 2015); resilience vs anticipation (e.g., De Bruijn et al. 2015). Some argue that resistance measures are an inherent part of resilience which reduces the need for capacity to absorb and adapt through a balanced resilience portfolio (Hegger et al. 2016; Restemeyer, Woltjer, and van den Brink 2015). Others argue that resistance is detrimental to the capacity to adapt, as resilience is cultivated through learning from the very same disturbance over time and ultimately leads to a false sense of security (Liao 2014).

However, upon reviewing this dichotomy it is evident that the understanding of resilience is contextual. For example, Owotoki et al. (2006), Mugume et al. (2015), and Balsells et al. (2013) argue that resistance is a key aspect of resilience as it aids in mitigating impacts; as opposed to probability, which promotes stakeholder decision making and capacity building of individuals, thus contributing to bottom-up resilience. On the other hand, Liao (2014) and Douven et al. (2012) view resistance as a separate concept and associate it with “flood control” strategies. They argue that flood control infrastructure (FCI) (or flood resistance) and urbanisation detriments the dynamics of floodplains in a multitude of ways. Namely, changes to sediment and flow, heightened flood risk in the long-term and degraded riverine ecosystems (e.g., decreased salmonids). Moreover, upon failure, the consequences are often worse, and that flood awareness and preparedness of those “protected” by the barrier is likely to be low. As Liao (2014, 735) summarises: “The idea that ecological impacts and flood safety are trade-offs has justified the management practice that prioritises flood control over ecological conservation and restoration.”

The stark contrast could, perhaps, be attributed to the spatial scale in which these two concepts are applied. The studies in which resistance is considered an integral part of resilience vary. Balsells et al. (2013) and Owotoki et al. (2006) focus on building and neighbourhood levels, where the FRM strategies are mainly small scale such as property retro-fittings (wet-proofing and dry-proofing), or green roofs and water attenuation systems. However, the studies in which resistance is viewed as undermining the concept of resilience, are applied at larger spatial scales where the adopted FRM strategies are on a grander scale, such as flood protection schemes (levees and dykes) that apply to a more regional level as opposed to local. Liao (2014) adds that a flood resistant approach has a negative effect on the long-term development of flood resilience, as it reduces the capacity for episodic learning. Tempels and Hartmann (2014) also highlight the need to move from resistance-based approaches to resilience-based approaches in the context of land-water boundaries. This “land-water boundary” concept perhaps allows for clearer explanation of the varying viewpoints of resistance vs. resilience and their relationship with spatial scales. To further highlight the
polysemic nature of resilience, the aforementioned papers define resilience and resistance inversely. Douven et al. (2012, 1290) define a resilience strategy as a way of *minimising the consequences of flooding* whereas Balsells et al. (2013) and Owotoki et al. (2006) define *resistance* in the same manner (where impacts are mentioned as opposed to consequences). Moreover, Chaidilok and Olapiriyakul (2017) include anticipation as an integral part of resilience, whereas De Bruijn (2004, 660) argues that anticipation is fundamentally the “antitheses of resilience.”

Restemeyer, Woltjer, and van den Brink (2015) question whether resilience vs resistance is an over-simplified dichotomy which further undermines the original understanding of resilience. For example, the authors argue that “persistence” and “robustness” are attributes of resilience, which are synonyms of resistance, indicating that resistance can be one important aspect of resilience. In line with this argument, Tempels and Hartmann (2014) state that there should be a balanced approach towards flexibility and robustness, as opposed to prioritising one over the other. Although De Bruijn et al. (2015) distinguishes anticipation from resilience, they argue that in the context of FRM, a hybrid approach may be more appropriate. This suggests that resilience should be considered as a dual concept, in which aspects are complimentary to each other, as opposed to polar opposites (see also van Ree et al. 2011; Manojlovic and Pasche 2008; Miguez and Veról 2017; McEwen et al. 2017). This duality implies that these authors have adopted a perspective of resilience that lies within two out of three resilience frameworks. Moreover, some authors take resilience a step further from a dual concept towards a tripartite concept in which resilience is an iterative cycle. Restemeyer, Woltjer, and van den Brink (2015) state that resilience demands all three aspects: robustness, adaptability, and transformability. Nguyen and James (2013) mention three common capacities of resilience: speed of recovery, magnitude of disturbance relative to a threshold, ability to learn/adapt/transform. Hegger et al. (2016) define resilience in terms of three capacities: capacity to resist; capacity to absorb/recover; capacity to transform. The commonality between studies that allude to resilience being a tripartite concept is the aspect of *transformation*, which emphasises that resilience is more than just mitigating impacts and probability – it is about encouraging the view that there is no end-point to resilience and that floods can be an opportunity.

Allowing small, manageable floods to enter the system allows adjustment and learning over time, increasing resilience capacity to cope with larger, unpredictable flood events (Liao 2014; Liao, Le, and Nguyen 2016; Adeyeye and Emmitt, 2017). As Liao (2014, 736) states: “resilience to a disturbance is cultivated through learning from and adapting to that very same disturbance over time”. Therefore, learning from these disturbances leads to genuine adaptation to floods and an opportunity for resilience (Nguyen and James 2013; Balsells et al. 2015; Thieken et al. 2014). Moreover, Odemerho (2015) argues that a complete lack of direct personal experience with flooding may constrain both understanding and motivation for taking personal or community actions, which are prompted by such an event. Liao (2014) identifies this as a research gap, where there is a need for a better understanding of the relationship between small frequent floods and flood risk awareness. Understanding floods as an opportunity is also contextual. For example, past flood events in Western countries have helped to improve recovery and mitigate the impacts of future floods. Conversely, Liao, Le, and Nguyen (2016) point out that flooding is a resource in Vietnam, as it provides an opportunity to increase livelihoods.
3.2. Resilience assessment approaches

In order to highlight the key methods used to assess resilience, methods are grouped into quantitative and qualitative and are further categorised as shown in Table 2.

3.2.1. Quantitative approaches

Outlined in this section are the quantitative methods that are grouped into either numerical-based or semi-quantitative approaches. Quantitative approaches accounted for 39% of methods used to measure and assess resilience in the reviewed literature. The most common quantitative methods of assessing resilience were simulation based and indicator based approaches. Simulation based approaches typically involved using hydraulic modelling software to simulate flood events as a means of analysing system performance (see Birgani and Yazdandoost 2016; Owotoki et al. 2006; Mugume et al. 2015; Schinke et al. 2016; Golz, Schinke, and Naumann 2015; Pregnolato et al. 2016; Gersonius et al. 2008). Alternatively, Coates et al. (2016) and Song, Huang, and Li (2017) use other simulation methods, such as Agent-Based Modelling and Change Detection Analysis, respectively. The indicator methods used are all similar in principle; however they are applied differently and can be easily tailored to different contexts and hazards across geographical boundaries. For example, Qasim et al. (2016) utilise indicators to provide a proxy measure of resilience in a Pakistani Province. Miguez and Veröl (2017), however, use indicators to measure relative resilience of design alternatives to determine which ones cope better with future conditions compared to baseline conditions. Moreover, Keating et al. (2017) use indicators to measure post-outcome resilience as a means of validating indicators as true measures of resilience.

3.2.2. Qualitative approaches

Qualitative approaches were found to be the dominant methods used for measuring resilience, accounting for 61% of adopted methods in the database. The qualitative methods are less diverse than quantitative methods included in this review as they are largely either descriptive interview methods or conceptual/theoretical frameworks. However, six studies were desk-based studies as opposed to either of the aforementioned approaches. Furthermore, these qualitative methods were often used in conjunction with each other. The most popular method overall was found to be interviews, accounting for 29% of methods in total. Following in popularity was conceptual/theoretical frameworks (20%). The emphasis on qualitative methods perhaps highlights that flood resilience is less expert-driven and technocratic than previous FRM strategies, with a shift now towards insights from those directly involved in floods. Furthermore, the popularity of conceptual and theoretical frameworks either highlights a need to – or difficulty in – operationalising resilience.

3.2.3. Spatial scale

Authors were grouped depending on their spatial scale of analysis, and were then classified as to whether they came from a technical or social perspective, a combination of both, or a strategic perspective (Figure 6). A key finding from the Morrison, Westbrook, and Nob (2017) review on the governance of FRM was the divide between
Table 2. Classification of resilience methods (asterisk next to source denotes studies that are in review format).

| Source                                                                 | Quantitative | qualitative |
|------------------------------------------------------------------------|--------------|-------------|
|                                                                        | Optimisation | Fuzzy       | Simulation | Indicators | Surveys | Interviews | Desk Study |
| Manojlovic and Pasche (2008)                                           | ✓            |             |            |            |         |            | ✓          |
| Douven et al. (2012)                                                   | ✓            |             |            | ✓          |         |            | ✓          |
| Oladokun, Proverbs, and Lamond (2017)                                  | ✓            |             | ✓          |            |         |            |            |
| Birgani and Yazdandoost (2016)                                         | ✓            |             |            |            |         | ✓          |            |
| Owotoki et al. (2006)                                                  | ✓            |             |            |            |         |            |            |
| Mugume et al. (2015)                                                   | ✓            |             |            |            |         |            |            |
| Schinke et al. (2016)                                                  | ✓            |             |            |            |         |            |            |
| Golz, Schinke, and Naumann (2015)                                      | ✓            |             |            |            |         |            |            |
| Pregnolato et al. (2016)                                               | ✓            |             |            |            |         |            |            |
| Gersonius et al. (2008)                                                | ✓            |             |            |            |         |            |            |
| Beheshtian, Donaghy, and Rouhani (2016)                                | ✓            |             |            |            |         |            |            |
| Song, Huang, and Li (2017)                                             | ✓            |             |            |            |         |            |            |
| Coates et al. (2016)                                                  | ✓            |             |            |            |         | ✓          |            |
| Miguez and Veról (2017)                                                | ✓            |             |            |            |         |            |            |
| Beevers, Walker, and Strathie (2016)                                   | ✓            |             |            | ✓          |         |            |            |
| Qasim et al. (2016)                                                   | ✓            |             | ✓          |            |         |            |            |
| Keating et al. (2017)                                                  | ✓            |             | ✓          |            |         |            |            |
| Chiang and Ling (2017)                                                 | ✓            |             | ✓          |            |         |            |            |
| Balica, Douben, and Wright (2009)                                     | ✓            |             | ✓          |            |         |            |            |
| Kotzee and Reyers (2016)                                               | ✓            |             | ✓          |            |         |            |            |
| Garvin et al. (2016)                                                  | ✓            |             |            |            |         |            |            |
| Batica and Gourbesville (2016)                                         | ✓            |             |            |            |         |            |            |
| de Bruijn (2004)                                                       | ✓            |             |            |            |         |            |            |
| Mavhura (2017)                                                         | ✓            |             |            |            |         |            |            |
| Bosher et al. (2009)                                                  | ✓            |             |            |            |         |            |            |
| Odemerho (2015)                                                        | ✓            |             |            |            |         |            |            |
| O'Sullivan et al. (2012)                                               | ✓            |             |            |            |         |            | ✓          |

(Continued)
| Source                                                  | Quantitative | Qualitative |
|--------------------------------------------------------|--------------|-------------|
|                                                        | Numerical    | Descriptive |
|                                                        | Optimisation | Questionnaire |
|                                                        | Fuzzy        | Surveys     |
|                                                        | Simulation   | Interviews  |
|                                                        | Indicators   | Desk Study  |
| Nguyen and James (2013)                                 | ✓            |             |
| Orr et al. (2016)                                       | ✓            |             |
| Restemeyer, Woltjer, and van den Brink (2015)           | ✓            |             |
| Restemeyer, van den Brink, and Woltjer (2017)           | ✓            |             |
| Ping et al. (2016)                                     | ✓            |             |
| Schelfaut et al. (2011)                                | ✓            |             |
| Cashman (2011)                                         | ✓            |             |
| Twigger-Ross et al. (2016)                             | ✓            |             |
| Keogh et al. (2011)                                    | ✓            |             |
| Cheshire (2015)                                        | ✓            |             |
| Balsells et al. (2015)                                 | ✓            |             |
| van Kessel, Gibbs, and MacDougall (2015)                | ✓            |             |
| McEwen et al. (2017)                                   | ✓            |             |
| Hegger et al. (2016)                                   | ✓            |             |
| Liao, Le, and Nguyen (2016)                            | ✓            |             |
| Borba, Warner, and Porto (2016)                        | ✓            |             |
| McGuinness and Johnson (2014)                           | ✓            |             |
| Johnson and McGuinness (2016)                           | ✓            |             |
| White et al. (2018)                                    | ✓            |             |
| Nie (2016)                                             | ✓            |             |
| de Bruijn et al. (2015)                                | ✓            |             |
| Tempels and Hartmann (2014)                            | ✓            |             |
| Balsells et al. (2013)                                 | ✓            |             |
| Lhomme et al. (2013)                                   | ✓            |             |
| Barroca and Serre (2013)                               | ✓            |             |
| Serre et al. (2018)                                    | ✓            |             |
| Hartmann and Scheibel (2016)                           | ✓            |             |
Table 2. (Continued).

| Source                                | Quantitative | Qualitative |
|---------------------------------------|--------------|-------------|
|                                       | Numerical    | Semi-quantitative | Descriptive | Frameworks |
|                                       | Optimisation | Fuzzy        | Simulation  | Indicators | Questionnaire | Surveys | Interviews | Desk Study | Conceptual/ Theoretical |
| van Ree et al. (2011)                 |              |              |            |            |              |         |            |            | ✓                      |
| Liao (2014)                           |              |              |            |            |              |         |            |            | ✓                      |
| Lhomme et al. (2010)                  |              |              |            |            |              |         |            |            | ✓                      |
| Adeyeye and Emmitt (2017)             |              |              |            |            |              |         |            |            | ✓                      |
| Albano, Sole, and Adamowski (2015)    |              |              |            |            |              |         |            |            | ✓                      |
| Chaidilok and Olapiriyakul (2017)     |              |              |            |            |              |         |            |            | ✓                      |
| Montgomery et al. (2012)              |              |              |            |            |              |         |            |            | ✓                      |
| Morrison, Westbrook, and Nob (2017)*  |              |              |            |            |              |         |            |            | ✓                      |
| Rose et al. (2009)*                   |              |              |            |            |              |         |            |            | ✓                      |
| Escarameia (2016)*                    |              |              |            |            |              |         |            |            | ✓                      |
| Hammond et al. (2015)*                |              |              |            |            |              |         |            |            | ✓                      |
| Thieken et al. (2014)*                |              |              |            |            |              |         |            |            | ✓                      |
| Kenna (2008)*                         |              |              |            |            |              |         |            |            | ✓                      |
| **Total**                             | 2            | 2            | 10          | 10          | 8            | 24       | 9          | 17          |                      |
the physical and social sciences. The tools in FRM were mainly physical-science based and where the aim was stakeholder engagement, social science techniques were used. There was some divergence in methods in this review depending on author perspective, which becomes more apparent at different spatial scales.

**Household-scale methods.** The most common approach to resilience was to measure, or assess in some form, property-level flood resilient technologies, the majority of which were technical methods such as flood impact assessments (see e.g., Owotoki et al. 2006; Gersonius 2008; Golz, Schinke, and Naumann 2015; Garvin et al. 2016). White et al. (2018) and Hartmann and Scheibel (2016) focus on property-level resilience measures, but concentrate on how to improve uptake. Other studies at this scale explore methods in order to understand the relationship between risk awareness/perception and resilience (see e.g., O’Sullivan et al. 2012; Rose et al. 2009). Only two of the studies at this scale explore resilience from an individual’s perspective, measuring the concept in terms of the resilience in which the individual’s themselves value (see e.g. Nguyen and James 2013; van Kessel, Gibbs, and MacDougall 2015).

**Community-scale methods.** At this scale, social science perspectives are more prevalent, which is reflected in the focus on qualitative methods (see e.g., Twigger-Ross et al. 2016; Liao 2014; Cashman 2011; Cheshire 2015) or semi-quantitative (Orr et al. 2016; Mavhura, 2017; Qasim et al. 2016; Schelfaut et al. 2011). On the other hand, methods which explored resilience at the community scale as a physical urban

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Figure 6. Papers classified depending on spatial scale of analysis and perspective adopted. (Those marked with an asterisk attempt to combine analysis across more than one spatial scale).
system include Balsells et al. (2013); Balsells et al. (2015); Serre et al. (2018) using qualitative methods. These models solely explored the interdependencies of technical systems. Manojlovic and Pasche (2008) explore flood mitigation strategies for communities based on the “living with floods” principle; however, the methodology for capacity building as well as political and social aspects are not discussed.

City-scale methods. The focus moves back towards technical tools to measure resilience at city scale, as illustrated in Figure 6. Despite the prevalence of physical tools for resilience at this level, there has been an attempt to overcome this siloing. Balica, Douben, and Wright (2009) develop Flood Vulnerability Indicators which include physical and social vulnerability. Beevers, Walker, and Strathie (2016) and Adeyeye and Emmitt (2017) combine both physical and social systems within their methodologies. Furthermore, strategic research starts to emerge at this scale (see e.g., Restemeyer, Woltjer, and van den Brink 2015).

National-scale methods. Methodologies which are exclusively from a social perspective appear to be lacking, whereas those from a strategic perspective are more prominent at this spatial scale than any other. Strategic papers explore the importance of institutional context when applying the resilience concept (e.g., Restemeyer, van den Brink, and Woltjer 2017; Hegger et al. 2016).

Cross-scale methods. A common theme across the methodologies in this review was to adopt a systems-thinking approach to resilience (34% of papers). Systems-thinking allows all interactions to be taken into account in a multiscale manner by focusing on interrelationships and feedback loops (Balsells et al. 2013; Mavhura 2017; Montgomery et al. 2012). Whilst each spatial scale has a clear influence on resilience, cross-scale interactions are important in understanding resilience, as changes in one scale can reflect the capacities and outcomes related to another scale (Mavhura 2017).

A few studies combine different spatial scales in their methods. Cashman (2011) evaluates the institutional response to a flood event at the city level as well as local initiatives in response to concerns expressed by communities. The interdependencies of these initiatives are analysed to show improvements in both social and institutional resilience, increasing overall societal resilience in the context of FRM. Hartmann and Scheibel (2016) discuss how the Flood Label tool to increase awareness at the property level needs to be embedded in a strategic governance arrangement to achieve flood-resilient cities. In a similar vein, Johnson and McGuinness (2016) adopt a systems perspective to understand business response to flood events, integrating macro (policy-level) and micro-level (mitigation measures) dynamics. Van Kessel, Gibbs, and MacDougall (2015) also utilise a systems approach to provide insights into the health resources that people value in supporting resilience. Whilst the study focuses on individual resilience, it explores the relationship between the individual and varying spatial scales of the city system. Aside from connecting the interdependencies of scales in the social system, Beevers, Walker, and Strathie (2016) and Adeyeye and Emmitt (2017) attempt to combine socio-technical interactions for a more holistic understanding of flood resilience at multiple scales.

3.2.4. Temporal scale

Of all capacities shown in Figure 4 that are considered to be aspects of resilience, recovery was the most widely cited of all, accounting for 49% of papers within the final database. The prevalence of this aspect was examined further and it was found that the 33 papers cited recovery in their adopted definition. Only 16 explicitly
measure or focus on recovery in their methods – split evenly between quantitative and qualitative methods. De Bruijn (2004) highlight that recovery is a complex resilience metric to quantify due to the variation in recovery rates within an FRM system. This implies that despite recovery being one of the most cited aspects it is considered the most difficult to measure.

Recovery processes which focus on the shorter-term are usually associated with “bouncing back” (Birgani and Yazdandoost 2016) or establishing pre-disaster conditions, and are associated with speed (Song, Huang, and Li 2017). The time in which recovery is measured can therefore be considered a metric of resilience. Only one of the 16 papers directly quantify recovery in a temporal sense. Song, Huang, and Li (2017) adopt a dynamic approach and measure immediate recovery over time through utilising big-data availability in China. Whereas, long-term recovery is mainly focused with the learning and adaptation process from the event (Nguyen and James 2013). Without this differentiation, measuring resilience as speed of recovery may not capture its full dimensions, as it misses the ability to learn and transform (Nguyen and James 2013). However, long-term recovery is not widely considered among the reviewed papers in this review. Keating et al. (2017) argue resilience measurement methods are lacking in empirical validation, as most methods only consider ex-ante resilience as opposed to ex-post resilience; therefore questioning the validity of measured resilience. The authors adopt a semi-quantitative indicator approach, and is the only paper that aims to validate resilience and consider long-term recovery by re-evaluating the robustness of indicators used two years after a flood event occurred. This review found a lack of clarity surrounding the temporal scales of resilience in this review, as only 37% of papers explicitly state the temporal scale to which resilience is being assessed.

3.3. Emergent themes for operationalising resilience

Restemeyer, Woltjer, and van den Brink (2015, 46) emphasise the importance of converting resilience from a concept into an operational framework, or defining resilience, to doing resilience. Several key themes which emerged from this review are discussed.

3.3.1. Paradigm shift

The resilience concept has emerged as a result of a paradigm shift within FRM. Traditionally, FRM has predominantly focused on “fighting the water” and “restorative resilience” (Odemerho 2015). This has resulted in a disconnect between human and natural systems which Marcus and Colding (2011) as cited by Adeyeye and Emmitt (2017, 499) refer to as environmental generational amnesia within city dwellers. This concept represents a lack of human knowledge of how to integrate the natural world into the urban environment, which subsequently leads to poorly integrated planning and misunderstanding of current and future flood risk. If when flooding is conceptualised as an opportunity for resilience rather than a disaster, the concept of living with floods becomes more apparent. Tempels and Hartmann (2014, 873) address this point by conceptualising the land/water boundary as a “fluid frontier” to understand the mutual influence and interdependencies of both ecological and human systems, shedding a new perspective on FRM for flexibility and reorganisation. Similarly, Restemeyer, Woltjer, and van den Brink (2015) argue that only when adjustments are made to both the physical and social environment can transformability occur, which
the authors interpret as the capacity to shift from “fighting the water” to “living with water.” Within this paradigm shift, there is a shift in responsibility from state protection to individuals taking responsibility for their own flood risk.

3.3.2. Context and scale

In Western countries with advanced engineering solutions, the legacy of restorative resilience has resulted in a state of dependency amongst the general public who perceive the government to be responsible for FRM (Hegger et al. 2016). The result is a reluctance amongst the public to take ownership of their own flood risk. Critics of this new approach have argued that such rescaling of resilience to the local level absolves the state from accountability: “failure becomes a property of those who fall victim” (Cheshire 2015, 1083). However, in Nigeria (Odemerho 2015) and Brazil (Borba, Warner, and Porto 2016) there is a lack of official technocratic FRM, and thus FRM tends to be the responsibility of communities. This could be indicative of the Global South where there has been no such paradigm shift in responsibility of FRM. Instead, past adaptation strategies become the database of local knowledge to guide a long-term framework of the future through an iterative learning process (Odemerho 2015). The participatory process allows translation of system feedback to be incorporated into new knowledge for further action. This contrasts with the Netherlands resilience policy which is dominant in its resistance-based approach, where the governance process remains expert driven and social learning is limited (Restemeyer, van den Brink, and Woltjer 2017). It is this gap between Nigeria and the Netherlands that highlights the importance of a balance between top-down and bottom-up governance: inadequate top-down governance in Nigeria during the 1980s resulted in devastating impacts in the 2012 floods, but also highlights the role that bottom-up FRM can play in cases where appropriate governance is lacking. Learning is argued as being a core component of resilience in this review, as it is fundamental to the ability to adapt and transform from a stress event such as flooding, and helps deal with uncertainty. Moreover, when operationalising resilience, spatial scale needs to be taken into consideration. At the finer spatial scale, it can be argued that the efficiency of resilience is better as local level adjustments can occur more quickly than at the national level as they are better suited to the local context (Liao, Le, and Nguyen 2016; Restemeyer, van den Brink, and Woltjer 2017).

3.3.3. FRM strategies

Bottom-up approaches may be important for community acceptance and translation of local concerns into FRM (Bosher et al. 2009; Odemerho 2015; Schelfaut 2011). Nguyen and James (2013), van Kessel, Gibbs, and MacDougall (2015) and Keogh et al. (2011) adopt a bottom-up approach to their resilience methodology by focusing on individual perspectives of resilience by those who have experienced flooding, as opposed to a top-down approach with pre-determined indicators to determine resilience. A similar bottom-up perspective is adopted by Rose et al. (2009) who focus on the “locus of control” (Rotter 1982), a psycho-social theory that can be related to resilience of individuals. The locus of control is a belief system that outlines “internal locus” and “external locus,” the former consists of those who perceive circumstances to be within their control, whereas the latter believe they are determined by external influences such as luck or religious entities. Rose et al. (2009) provide examples of positive correlations between the locus of control theory and adaptive behaviour in the event of disasters. In
addition, results from Qasim *et al.* (2016) reinforce this theory, as it is found that the majority of the surveyed population within the study showed low preparedness and mitigative behaviour, as it was the belief that floods are a result of Allah’s will – thus further confirming the correlation between external locus’ and adaptive behaviour.

On the other hand, top-down approaches are still essential as part of a resilient FRM strategy. Property-level flood resilient technologies have become increasing integral to the new FRM paradigm. A theme of trust emerged in the literature surrounding the uptake of resilience measures. White *et al.* (2018) found that trust (or lack thereof) was an important influence in the uptake of private mitigation measures. For example, there is a lack of trust in the independence of manufacturing companies, in product performance, and in risk assessments. Furthermore, trust between citizens and people of influence in FRM was deemed to be an important factor in building resilience (Twigger-Ross *et al.* 2016; Manojlovic and Pasche 2008; and Schelfaut *et al.* 2011). A similar conclusion was drawn from the Water Management Enquiry, where relationships of trust were built between the public and key agencies which fostered social capital and therefore resilience (Cashman 2011).

Despite the importance of trust between the public and key stakeholders, a review of FRM governance by Morrison, Westbrook, and Nob (2017) highlights siloing between social and physical sciences. This is attributed towards low connectivity between stakeholder engagement, which focuses on social interactions such as trust, and the tools used in FRM governance, which are focused on the prediction and modelling of flood events and physical vulnerability. Further division in FRM governance relates to effectiveness of flood resilience technologies at property level. Due to lack of regulations surrounding FReT at National or European level, a lack of uptake in protective measures among homeowners exists (Golz, Schinke, and Naumann 2015). Coaffee (2008) as cited in Bosher *et al.* (2009, 18–19) further highlight the low connectivity between stakeholder engagement and governance of FRM as a result of the resilience agenda being developed: almost exclusively by politicians and emergency planning professionals with little if any discussion with citizens, the business community, town planners, urban designers and other built environment professionals.

### 4. Discussion

As a result of this review, while we would agree with Tempels and Hartmann’s (2014) proposition of a co-evolution between social and natural-physical systems as a way of improving resilience, we would further propose that a “fluid frontier” between top-down and bottom-up flood risk management is also necessary. On one hand, White *et al.* (2018) highlight that small-scale flood resilient technologies such as property-level protection are less prevalent in the Netherlands due to the reliance on large-scale flood defences. Furthermore, Gersonius *et al.* (2008) point out that due to strict building codes, small-scale resilience technologies are actively discouraged. This approach to FRM aligns with the “fighting floods” paradigm and is largely considered to be a top-down, technocratic strategy. On the other hand, Odemerho (2015) argue that a lack of institutional and governmental guidance forces a bottom-up approach to FRM that is less dependent on flood-resistant technology, and largely dependent on local knowledge at community level. Odemerho (2015, 140) argue that bottom-up FRM for resilience could become the “future recipe” in low and middle income countries. Interestingly, Schelfaut *et al.* (2011) and O’Sullivan *et al.* (2012) share this viewpoint.
from a European perspective, as bottom-up involvement is considered the most important resilience-relevant measure with regard to: interplay of institutions, flood risk communication and flood modelling tools. These arguments highlight that resilience is not a static concept, but one which is dynamic and fluid. Technocratic approaches to FRM would benefit from bottom-up approaches and vice-versa. Where an FRM strategy is positioned on the fluid frontier will be dependent on context (e.g., governance, institutional, geographical, historical etc.).

It is evident from Section 3.3.2 that resilience is highly context dependent with no single approach to universal resilience emerging. When comparing the FRM strategies for England and the Netherlands it becomes clear that resilience is subjective. On the one hand, the Netherlands can be perceived to be resilient to flooding because they are highly advanced in their ability to control flooding, leading to less frequent flooding and lower flood damage compared to England (Hegger et al., 2016). This has led Restemeyer, van den Brink, and Woltjer (2017) to question the usefulness of resilience if existing systems are already advanced in managing flooding. On the other hand, England could be perceived to be more resilient to flooding due to its high capacity to absorb and adapt to flooding, allowing England to perform well in terms of response and recovery (Hegger et al., 2016). We would argue that not one perspective is necessarily ‘more resilient’, but instead emphasises the fluidity of the concept, where certain aspects of resilience are prioritised depending on their relative importance. These contextual differences are also present on a more global scale. Liao, Le, and Nguyen (2016) highlight that despite lack of flood control infrastructure in Vietnam, hamlets remain functional at up to 2 m of flood water and for more prolonged periods of time. This shows a stark contrast in coping ability and adaptive capacity between Vietnam and Europe, as flood depths as high as this would likely devastate cities in Europe (Liao, Le, and Nguyen 2016). Furthermore, the public understand the benefits of flooding as opposed to the negative images which dominate Western media; and timely adjustments are formed by learning from floods at the local scale as opposed to the national scale (Liao, Le, and Nguyen 2016). Again, the relative importance of resilience aspects is further emphasised. A lack of institutional and governmental influence in countries such as Vietnam and Nigeria has elicited a more adaptive perspective on resilience as opposed to a more controlled approach. We are not romanticising either approach or perspective, instead encouraging the need for a fluid frontier between top-down and bottom-up resilience strategies. This reinforces the importance of addressing the question of resilience of what, to what (Carpenter et al. 2001)? By doing so, context is being explicitly considered in resilience strategies.

The lack of fluidity between perspectives of resilience has led to a clear divide in opinion as to whether there should be a united definition of resilience in order to make it more operational, or whether a single definition is undesirable. On the one hand, it is argued that no agreed definition of resilience makes it difficult to measure (Song, Huang, and Li 2017; Balsells et al. 2013; De Bruijn 2004). On the other hand, a single understanding of resilience is argued to be undesirable, where the multiple frameworks to measure resilience should be seen as a positive thing towards understanding and operationalising the concept (Hegger et al. 2016; Keating et al. 2017). We would agree with the latter, and add that whilst the three stages of resilience should be accounted for when applying the concept, these will naturally vary in importance – and methods of operationalising resilience should be consistent with this. This review found that 9% of resilience definitions account for engineering and complex adaptive systems aspects.
in their definition, without accounting for any systems aspects. We argue that such a sharp increase in complexity does not align with the full resilience concept – as it suggests that it is possible to bounce-back to the status quo as well as to a radically new way of operating as the complex adaptive systems aspects imply, without acknowledging the intermediate stage of complexity. Whilst this finding pertains strictly to the definitions used, we argue that this is the danger of restricting the resilience concept to a single definition. Given that a definition aims to provide disambiguation, we find ourselves presented with a resilience paradox in which the opposite occurs. A single definition coerces linear thinking, which is the antithesis of resilience and its associated complexity. The wider disaster-resilience research has also found that a lack of consistency between methods of assessing resilience and the concept itself has made resilience difficult to operationalise (see e.g., Henry and Ramirez-Marquez, 2012). Moreover, Rose (2007, 384) argues that without consistency, “resilience is in danger of becoming a vacuous buzzword from overuse and ambiguity.”

A lack of fluidity was also found between spatial scales when measuring resilience. We find that there is a bias towards either quantitative or qualitative methods of assessing resilience between spatial scales. For example, technical methods that assess the physical system are more prevalent at the household scale, whereas qualitative methods that examine the social system are favoured more at community level. Moreover, only 34% of papers adopt a ‘systems approach’ to assessing resilience, highlighting a lack of interconnectedness of resilience across spatial scales, thus leading to difficulty in operationalisation. Morrison, Westbrook, and Nob (2017) also find a siloing of methods for assessing resilience in FRM between physical and social sciences, which allows for a deeper insight into the segregation between physical and social systems.

Linking all three frameworks of resilience is the aspect of recovery. This review found recovery to be the most cited aspect of resilience. However, we would argue for an explicit differentiation of what authors mean by recovery by again acknowledging the context in which they are applying the resilience concept. For example, when applying resilience in the engineering or systems framework, resilience is often associated with speed of recovery. However, for complex adaptive systems, focusing on measuring the speed of recovery as a resilience assessment misses the ability to transform from a flood event into a new, less vulnerable state. This opens up the debate as to whether it is fruitful to measure recovery as an aspect of resilience, or whether recovery should be a continuous process of learning and transforming.

In order to achieve consistency, when considering resilience in FRM, temporal and spatial scales should be explicitly acknowledged within resilience research. Keating et al. (2017, 80) highlight that common challenges in resilience measurement frameworks are: “(1) defining an appropriate scale of analysis both geographically and temporally – specifying boundaries such as ‘resilience of what to what?’ – and (2) identifying the potential end users (‘indicators for whom?’) and potential purposes (‘indicators for what?’)”. By doing so, the resilience concept can work towards becoming more operational.

5. Research agenda

It is widely accepted that flooding cannot always be prevented, but flood impacts can be mitigated or reduced by adhering to resilience principles such as adequate preparation, or learning from past events. The three resilience frameworks presented by Martin-Breen and Anderies (2011) provide an understanding of the different aspects of resilience and
temporal scales that influence a variety of perspectives. We argue in this review that resilience should be considered as a tripartite concept that is considerate of all three frameworks; however we acknowledge that depending on the scale of application, certain aspects and frameworks may be more desirable or applicable than others. Over-emphasis on finding a united definition of resilience fails to acknowledge the fluidity of the concept. Considering resilience as a tripartite concept allows diversification by acknowledging that there are different ways to be resilient depending on context.

Moreover, without accounting for the slower dynamics of resilience, the complex adaptive systems framework, which considers adapting and transforming as fundamental aspects of resilience, is neglected. Meffe (2001), and Manfredo and Dayer (2004) both stress the importance of considering the impact of resilience at different spatial scales, for example, the study of individual resilience can drive the understanding of resilience at greater spatial scales. This highlights the interconnectedness between scales and how dynamics at one level may propagate upwards (or downwards) to another. For example, inconsistencies were found between methods of assessing resilience and the spatial scales at which they were applied. We find that studies which focused on resilience at the household scale were biased towards technical approaches as opposed to social – with the exception of Rose et al. (2009) and van Kessel, Gibbs, and MacDopugall (2015). In order to account for more social aspects of flood resilience, future studies could consider how household behaviour influences the level of resilience over time. Creating a fluid frontier between bottom-up and top-down strategies will encourage the integration of social and technical systems.

This review found only two methods which integrate social and technical systems across different spatial scales, and a disconnect between bottom-up and top-down FRM strategies. Therefore, a future research direction should be the development of a complex adaptive systems approach which accounts for the interdependencies between spatio-temporal scales, and couples human and physical systems to allow for new dynamics to emerge. An understanding of how these system dynamics emerge will elicit the transformative aspect to become operational, improving longer-term resilience. Thus finally, we argue that future research should move away from a reductionist approach to resilience and embrace its complexity.

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