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From managing risk to increasing resilience: a review on the development of urban flood resilience, its assessment and the implications for decision making

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Abstract. Driven by urban growth in hazard prone areas such as along coasts or rivers as well as by climate change induced sea-level rise and increase in extreme rainfall, flood risk in urban areas is increasing. Better understanding of risks, risk drivers and its consequences in urban areas have revealed shortcomings in the existing flood risk management approaches. This has led to a paradigm shift in dealing with floods from managing the risk to reduce damages, to making urban communities resilient to flooding. Often described as a complex and at times confusing concept, this systematic review identifies and summarises the different dimensions and approaches of urban flood resilience and how they are applied in practice. Our analysis shows that urban flood resilience as a concept has evolved over the last two decades. From an engineering concept with a strong focus on ensuring that the built environment can withstand a flood to a more recent definition as a transformative process with the aim to enable all parts of the urban system to live with floods and learn from previous shocks. This evolved understanding is also reflected in the increasing number of dimensions considered in urban flood resilience assessments and decision support tools. A thematic analysis of the challenges in conceptualising and applying urban flood resilience reported in the literature has revealed a number of issues including around fairness and equity of the applied approaches, a lack of data and widely accepted methods as well as uncertainty around changing risks as a result of climate change. Based on these findings we propose a new research agenda, focusing on meta studies to identify the key dimensions and criteria for urban flood resilience, supporting a transparent and evidence-led operationalisation.

Keywords: flood resilience, urban, decision making

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1. Introduction

Currently over 50% of the global population live in urban areas and the share is expected to increase to 68% by 2050 (UNDESA 2018). With a high concentration of people and assets as well as often being located in hazard prone areas, urban areas are particularly susceptible to the impacts from from flooding and other natural hazards such as earthquakes, storms or heat(Gu 2019). With over USD 651 billion in economic losses and 1.65 billion people affected between 2000 and 2019, flooding is the most damaging and widespread natural hazard globally (UNDRR 2020). In many urban areas across the world, flood risk is projected to increase through a combination of urban growth with new settlements in flood prone locations as well as increases in frequency and magnitude of flood events as a result of climate change (Westra et al. 2014, Vousdoukas et al. 2018). In Europe for example, Wolff et al. (2020) estimate an increase of flood exposure in coastal cities of up to 104% driven by sea-level rise and urban growth, while Guerreiro et al. (2018) find that the 10-year high flows of rivers in several European cities are likely to increase by 50% before 2100.

Devastating flood events in urban areas over the last decades with flood defence infrastructure being overwhelmed or failing, have highlighted shortcomings of current flood protection approaches. These events have triggered a paradigm shift in how to deal with floods (Manyena et al. 2011, Keating et al. 2016). From an early fatalistic view of seeing floods as unpredictable 'acts of god', to the building of large flood defence infrastructure in the 20th century with the goal to keep the water out of urban areas, limits in the predictability of flood hazards and the effectiveness of flood defences are now increasingly acknowledged in flood risk management (Reynard et al. 2017).

In this context, resilience has emerged as a key concept for managing floods. First defined in ecology by Holling (1973), the term resilience is now frequently used in disaster risk management among other fields such as sociology or psychology. Depending on the context and discipline, resilience has been defined in numerous ways. Definitions range from "withstanding a shock" (Ernstson et al. 2010) to "learning from mistakes" (Berkes 2007) to "bouncing forth" (Manyena et al. 2011).

With this wide range of conceptualisations of resilience in disaster risk research and over 70 published definitions of resilience in the scientific literature (Fisher 2015), the flexibility of the term resilience is described as both its biggest strength and weakness. While it is often argued that the lack of a unified definition of resilience makes it difficult to compare, measure and assess disaster resilience (De Bruijn 2004), others argue that the multiple definitions support a deeper understanding and ultimately a better operationalisation (Hegger et al. 2016, Keating et al. 2016).

In this context, a challenge frequently raised in the disaster risk management literature is the overemphasis on defining resilience rather than "doing" resilience, meaning to find, assess, implement and evaluate approaches that are able to reduce the negative impacts of flood events in practice (Restemeyer et al. 2015). Additionally, Wisner (2020) points out that the fuzziness of the concept bears the risk of being misused to off-load the duty of care of states and governments towards vulnerable groups and communities by overemphasising their responsibility in both risk creation and risk reduction.

This review therefore focuses on the operationalisation and application of urban flood resilience concepts and definitions , building on previous reviews (McClymont et al. 2020, Fenner 2020). The analysis considers only papers and studies that directly demonstrate the applicability of the introduced urban flood resilience concept, framework or tool. The applicability can be demonstrated through a case study, reflections on the data requirements (or other inputs), the intended outcomes and/or how the outcomes are used in practice.

The review aims to provide a better understanding of the different dimensions of resilience that are covered in existing frameworks, tools and approaches. The review looks at how those dimensions have been applied and the challenges that are reported when operationalising the underlying flood resilience concepts in urban areas. This includes the application of new tools, metrics or approaches to assess or measure the current flood resilience in an urban area as well as planning or decision support systems with the goal to increase urban flood resilience. It further aims to answer the question on what challenges and knowledge gaps still need to be addressed to match the theoretical ambition of flood resilient urban areas with the practical implications of decision making and planning in flood risk management. The review draws on studies from multiple disciplines ranging from risk governance and urban planning to engineering and hydrology to cover the multiple dimensions and the challenges of enhancing urban flood resilience.

The paper is structured as follows: chapter 2 describes the theoretical concepts of resilience used in this review including the most common flood resilience definitions and what they mean in an urban context. Chapter 3 describes the methodology of the systematic review, the search strategy as well as the applied frameworks and lenses to structure the search results. In chapter 4 the results of the systematic review are presented including a breakdown of the different operationalisations of urban flood resilience depending on the underlying theoretical concepts, the methodological approach as well as the intended outcomes. The result section also provides a summary of the most reported common challenges when applying the different resilience concepts in urban flood risk management. Chapter 5 discusses the findings and the identified gaps that currently hinders a full operationalisation of the theoretical concepts of urban flood resilience as well as its implications for decision-making. In chapter 6 the key findings of the paper are summarised, and a future research agenda is proposed.

2. Urban flood resilience

This review aims to summarise the literature on the different approaches to urban flood resilience originating in various combinations of conceptualisations of urban systems and disaster resilience. We focus on urban flood resilience approaches that demonstrate their operability through case studies, structure and summarise their challenges and analyse how these are addressed.

In the disaster risk management and disaster risk reduction literatures various definitions of resilience are used. Previous literature reviews have structured and categorised the different resilience definitions. A popular taxonomy of flood resilience based on a literature review by Martin-Breen & Anderies (2011) uses three main categories of resilience definitions: *engineering resilience, systems resilience, and complex-adaptive systems*. Other categories of resilience definitions mentioned in the literature include ecological resilience, socio-economic resilience (Douven et al. 2012) and cultural-institutional resilience (Ghasemzadeh et al. 2021). While those additional categories highlight important aspects of resilience, we follow McClymont et al. (2020) in using the three categories of Martin-Breen & Anderies (2011) as a robust and established taxonomy to classify resilience definitions. The three categories are described as follows:

Engineering resilience is often referred to maintaining the status quo or quickly returning to the status quo by withstanding a shock without permanent damage or distress. It is not exclusively applied in engineering (e.g. when describing the properties of a building), but also to describe the ability of a system to "bounce back" to its previous state i.e. a full recovery quickly after a shock (e.g. a flood event).

Systems resilience is similar to engineering resilience in terms of its aim to reach the initial pre-event stage after a shock. However, it also includes the ability of a system to remain functioning throughout the shock. To distinguish it to engineering resilience it is often described as "bouncing forth" to reflect the ability of a system to adopt throughout a shock or disruption to maintain its functionality.

Complex-adaptive systems resilience describes the ability of a system to adapt and transform to a new (and improved) stage. It describes the ability of a system to withstand and recover from a shock as well as learn from it to reach a new state. It is often associated with the longest timeframes of the three types of resilience as it describes an iterative, transformative learning process with the goal of a long-term increase in resilience.

In urban areas, engineering resilience plays an important role regarding the safety of the built environment. Setting and implementing design standards ensure that buildings and flood defences remain safe during and after a flood. Tragic flood disasters where buildings collapsed because safety standards have not been met (for example in informal urban settlements) underline the importance of engineering resilience in urban areas (Taş et al. 2013). Systems resilience in the context of urban flooding can mean that critical urban infrastructure such as schools or hospitals are either designed in a way that they remain functional while they are flooded or that there is an existing continuation strategy to ensure its operation e.g. from a flood safe location (Liao et al. 2016). Approaches that include a holistic adapted urban planning and design fall under complex-adaptive systems resilience. Examples in the literature and in practice include nature-based urbanism which aims to reduce flood risk for example through green spaces (Roggema 2020). This not only reduces the impacts from flooding through increased infiltration, but aims to holistically improve the quality of life in urban areas through co benefits such as improved air quality.

As hubs of economic activity, technology, and innovation urban areas play an important role in supporting the broader response to flood risks beyond the boundaries of cities. At the same time, rapid urbanisation, economic transformation and increasing socio-economic vulnerability of cities can increase the sensitivity and weaken the coping and adaptive capacities of urban communities in response to flood risks (Mehryar et al. 2022).

Figure 1 summarises and highlights the nested multi-layer structure of flood resilience in urban settings. Urban areas can be understood as multiple complex self-organising systems (social, economic, ecological systems), that through interaction have qualities that may not be present individually (Da Silva et al. 2012). This complexity leads to a unique set of challenges when it comes to implementing the aforementioned resilience concepts. Challenges include complex decision-making processes in a multi-layer urban governance structure, space constraints in urban planning as well as an urban design legacy that makes structural improvements complex and expensive (Marcus & Colding 2011, Adeyeye & Emmitt 2017). This review structures and summarises how these challenges are addressed in the literature to increase flood resilience in urban areas.

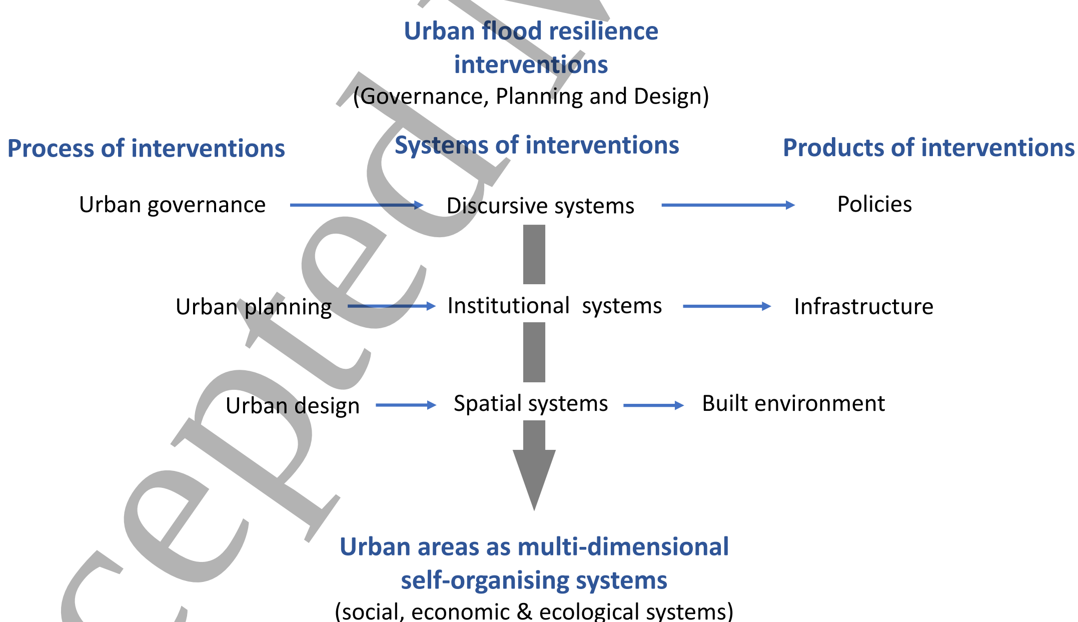

Figure 1. Nested layers of urban systems, entry points for urban resilience interventions and the corresponding products of interventions. The intersection between the nested layers and the multiple self-organising systems (social, economic, ecological) of urban areas define the multi-dimensional space in which urban flood resilience interventions are implemented. Adapted with permission from Marcus & Colding (2011)

3. Methods

3.1. Search strategy

Following the approach of previous systematic reviews such as by Ford et al. (2011), Righi et al. (2015), McClymont et al. (2020) and Deubelli & Mechler (2021), we set pre-defined eligibility criteria and do a systematic search using the Clarivate (formerly Thompson Reuters, ISI) Web of Science (WoS), and Elsevier Scopus citation databases to identify potential papers and other publications to be included in the review. The search process is outlined in Figure 2. We initially use the following search terms to scan the literature on 'urban flood resilience' using the WoS and Scopus databases, respectively:

TOPIC(Resilien* AND Flood) AND (Urban OR City OR Cities));

TITLE-ABS-KEY((Resilien* AND Flood) AND TITLE-ABS-KEY(Urban OR City OR Cities)).

Sampling the results of different search strings using the keywords *urban/city* and *flood resilience* we found the search string above to most comprehensively identify the relevant literature. However, due to the wide variety in publications on the topic of resilience, the search strings led to a high number of false positive results requiring a rigorous ex-post filtering of the search results. The terms were searched in November 2021. Although there was no lower date set when searching the WoS and Scopus databases, no relevant studies with publication dates prior to 2007 were found. Only articles published in English were considered and the search was narrowed down to the following (sub-)disciplines based on the number and relevance of the search results: *Environmental Sciences & Ecology, Water Resources, Science & Technology, Meteorology & Atmospheric Science, Geology, Engineering, Urban Studies, Public Administration, Geography, Business & Economics, Public Health, Development Studies, Social Sciences, Computer Science, Physical Geography, Transportation, Remote Sensing, Fuels & Energy and Construction & Building Technology.*

The search results include both the scientific literature such as journal articles, book chapters or books, as well as the grey literature such as published reports and working papers. The search with the criteria outlined above resulted in 1432 search results in the WoS database and 1425 search results in the Scopus database. After merging the search results from the two databases and removal of duplicates (N = 1816), abstracts were scanned manually for the pre-defined eligibility criteria (see Figure 2) to answer the research questions outlined in the introduction. This means only papers are included in the systematic review which are dealing with the topic of urban flood resilience and can demonstrate the applicability of the outlined concept, framework or tool through for example a case study, reflections on the data requirements (or other inputs), and/or the intended outcomes or how they are used in practice. While this includes papers without a fully documented (practical) implementation, papers solely focusing on the conceptualisation or definition of urban flood resilience are excluded from the review. The selected papers do not require to have their own definition of urban flood resilience but can also built on existing definitions or conceptualisations of resilience. In case the same framework, tool or approach is applied in several papers, they are counted as separate publications as long as they are applied in different case studies.

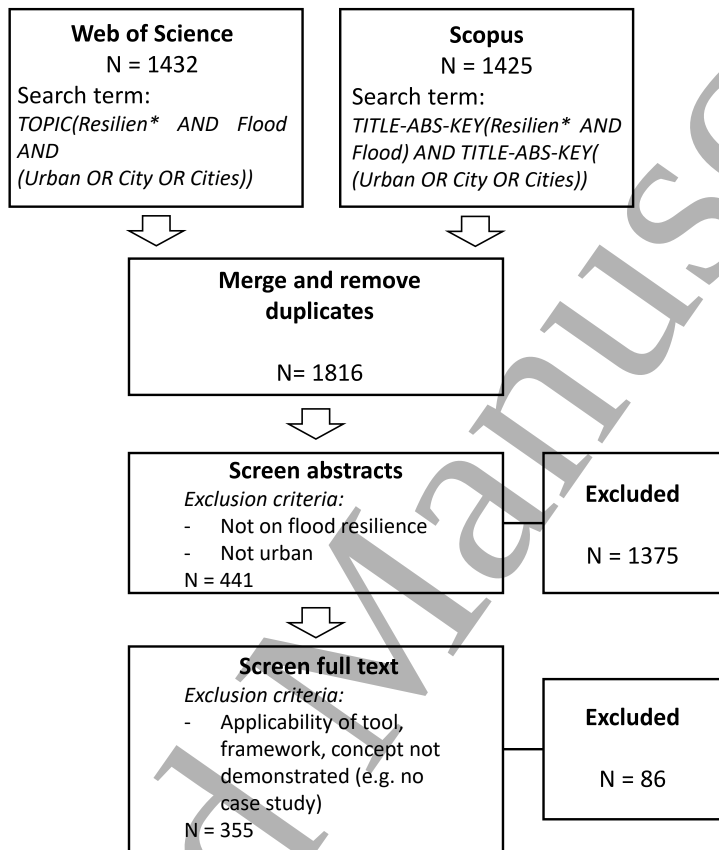

Figure 2. Search strategy for the systematic review of the literature on urban flood resilience

3.2. Bibliometric analysis

A descriptive bibliometric analysis of the urban flood resilience literature is conducted to outline its development since the concept has emerged in the literature in the mid-2000s including the number of publications, the fields of research and the geographical areas covered by the case studies mentioned in the literature. To systematically explore the different aspects of urban flood resilience and to identify potential trends and gaps in the literature, we structure and group the pre-screened publications along a number of different dimensions and lenses.

Definition of urban flood resilience: As described in chapter 2, an important distinction guiding the direction of research is the definition of urban flood resilience used in a study. Following the taxonomy established by Martin-Breen & Anderies (2011) and used by McClymont et al. (2020), we classify the relevant literature into three types of definitions of urban flood resilience: *engineering resilience, systems resilience*, and *complex-adaptive systems* (see chapter 2 for a detailed description). Quotes from key publications on urban flood resilience are selected to underline the conceptual differences between the three types of definitions.

Properties of urban flood resilience: Closely linked to the definitions of urban flood resilience are the properties that characterise flood resilience in urban areas. To structure these properties, we use an established framework describing (flood) resilient systems. Originally developed in the context of earthquake engineering resilience and later adapted to (urban) flood resilience is the 4R framework describing the four key properties of resilience: *robustness* or the physical strength of components such as infrastructure; *redundancy* or the substitutability of those components; *resourcefulness* or the ability to mobilise resources; and *rapidity* or the ability to return to the pre-disturbance state in a timely manner (Bruneau 2006, Liao 2012, Mochizuki et al. 2018).

Capitals of urban flood resilience: The sustainable livelihoods framework is used as a second lens to analyse urban flood resilience on a systems level. The sustainable livelihoods framework considers five capitals (5Cs) to describe the flood resilience of an (urban) community: the *physical capital* or the build environment and technical facilities, *human capital* or the demographics, skills and knowledge of a community, *social capital* or the formal and informal support networks in a community, *financial capital* or the financial security and protection of a community and *natural capital* or the natural environment relevant for flood protection and mitigation (Keating et al. 2017).

Spatial scales of urban flood resilience: The final lens applied is spatial scale in urban flood resilience assessments. The spatial scale analysed ranges from individual households as the smallest unit to assessing urban flood resilience of cities as a whole, often covering multiple scales at the same time to address the multi-layer challenge of urban flood resilience (see chapter 2 and Figure 1).

All dimensions and its characteristics considered in the structured analysis are summarised in Table 1. The 4R and 5C frameworks are used to explore the characteristics of urban flood resilience that are most frequently addressed in the literature including the links and relationships between those characteristics. Univariate frequency analyses are conducted for each of the 4Rs and 5Cs as well as bivariate frequency analyses to identify pairs of properties most frequently addressed together.

The analysis also aims to identify less frequently addressed characteristics and/or gaps in the urban flood resilience literature.

3.3. Thematic analysis

Using thematic analysis, a semi-structured, qualitative approach, the literature on urban flood resilience is reviewed for common challenges, both in regard to the concept and

Table 1. Overview of the different lenses and analytical frameworks used to analyse the urban flood resilience literature

Lens	Characteristics/Properties	Literature
Definition of urban flood resilience	- engineering resilience - systems resilience - complex-adaptive systems	Martin-Breen & Anderies (2011) McClymont et al. (2020)
4R resilience framework	- robustness - redundancy - resourcefulness - rapidity	Bruneau (2006) Liao (2012) Mochizuki et al. (2018)
5C sustainable livelihood framework	- physical - human - social - financial - natural	DFID (1999) Keating et al. (2017)
Spatial scale of assessment	- household - neighbourhood/community - city	Marcus & Colding (2011) McClymont et al. (2020)

its implementation. In the analysis, descriptive and analytical themes are formed until inductive thematic saturation is reached, meaning that no new codes or themes can be derived from the reviewed literature (Saunders et al. 2018). The thematic analysis is conducted following a six-phase process as outlined by Braun & Clarke (2006) : after familiarising with the identified literature (phase 1), initial structuring criteria are selected including the type of study (e.g. technical assessments or decision support tools), the definition of resilience used as well as the inputs and outputs of a study (phase 2). Based on the initial criteria, common challenges regarding the concept of urban flood resilience and its implementation reported in the literature are collated (phase 3) and reviewed (phase 4). The finalised themes are then named (phase 5) and reports for each of the themes are produced highlighting specific aspects of each theme in context of the different types of studies in the urban flood resilience literature.

4. Results

4.1. Systematic search results and bibliometric analysis

Based on the search of the Scopus and WoS literature databases and the filtering of the literature as described in chapter 3.1 and Figure 2, 355 publications, published between 2007 and 2021 were selected for the bibliometric analysis.

Figures 3 (A)-(C) show the distribution of publications over time. Both the search results (Figure 3A and B) as well as the selected publications (Figure 3C) have increased over time, with a noticeable increase in the number of relevant publications from 2016 onwards. This timeline aligns with flood resilience raising on the global agenda with key global agreements reached in 2015 such as the Sendai Framework for Disaster Risk Reduction, reiterating the commitment to building disaster resilience, the Paris Agreement defining a global goal on "enhancing adaptive capacity and resilience" and the launch of the Sustainable Development Goals (SDG) including SDG 11 – "Making cities and human settlements inclusive, safe, resilient and sustainable". Following these international agreements, several global initiatives and humanitarian organizations such as the World Resources Institute, ARUP, UN office for Disaster Risk Reduction, and Asian Cities Climate Resilience Network, together with national and regional governments have started to collaborate with cities across the world, developing versions of urban resilience frameworks, tools, and approaches to assess the resilience of cities against extreme weather events and wider impacts of climate change, including flooding (Laurien et al. 2022).

The identified literature on urban flood resilience is predominantly coming from the fields of *Environmental Science & Ecology* as well *Water Resources*. However, there is a large cumulative number of publications from a wide range of disciplines including *Meteorology & Atmospheric Science* to *Engineering, Urban Studies* and *Other Social Sciences* underlying the multi-disciplinarity of urban flood resilience as a topic (Figure 4).

Figure 5 shows the geographical region of case study area(s) mentioned in each publication by year of publication. Europe and Central Asia were the dominate region for case studies in the earlier part of the study period from 2008 to 2014. Publications with case studies either from Europe & Central Asia or East Asia & Pacific have both increased significantly in number over the study period. The dominant case study region for publications on urban flood resilience is now East Asia & Pacific, mainly driven by studies on Chinese cities. Publications with case studies from North America have started to occur frequently from 2015 on-wards and are increasing since then. Studies on South Asia have been almost non-existent for most part of the study period but have recorded a significant increase in numbers between 2020 and 2021.

4.2. Definition, scale and dimensions of urban flood resilience

Definitions of urban flood resilience: Table 2 shows a summary of the three categories of resilience definitions outlined in section 2, alongside quotations exemplifying how they are described in the literature and their share in the reviewed literature. With 249 out of 354 of identified publications (70%) using a *Systems resilience* definition, it is the predominant category of resilience definitions in the reviewed literature. This followed by 18% of publications in the reviewed literature using *Complex-adaptive systems* resilience definitions. Only a small part of reviewed literature (12%) uses *Engineering resilience* definitions.

Figure 6 shows how the distribution between the three categories of resilience definitions has changed over the study period. Publications using *Engineering resilience* definitions have dominated the urban flood resilience literature at the beginning of

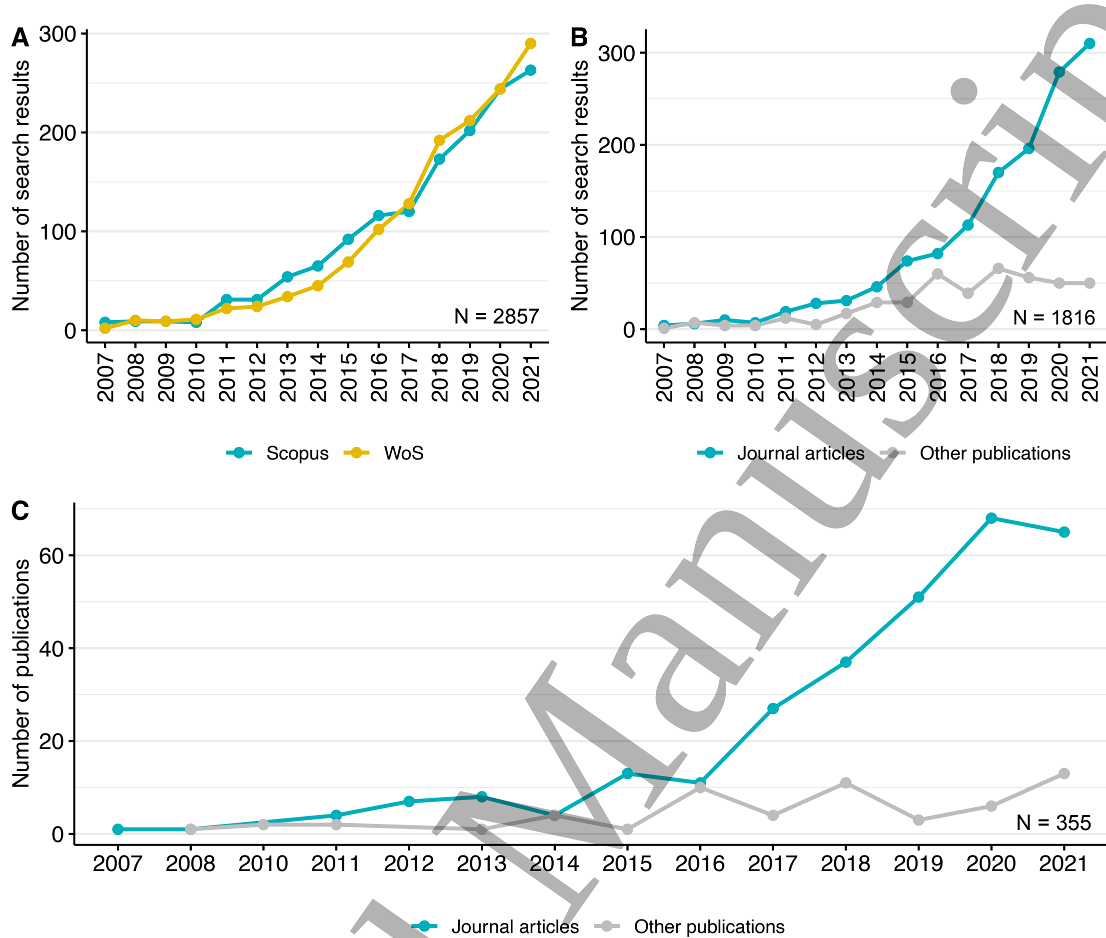

Figure 3. (A) Distribution of total number of search results from Web of Science (WoS) and Elsevier Scopus by year (N = 2857). (B) Distribution of total search results from journal articles (WoS and Scopus, duplicates removed) and other publications by year (N = 1816). (C) Distribution of reviewed and selected search results of journal articles (WoS and Scopus) and other publications by year (N = 355).

the sampling period, but have been less frequently used in literature since then. The corresponding increase in the share of publications using a *Systems resilience* definition indicates that the shift to more complex resilience definitions is part of a evolution that has happened since the concept of urban flood resilience has first emerged in the literature. *Complex-adaptive systems* resilience definitions have only recently gained traction with the share of reviewed publications increasing since 2015.

The increasing complexity in resilience definitions is illustrated through examples in Table 2. Publications using an *Engineering resilience* type definition, mostly focus on technical solutions that can often be directly implemented with the goal to support urban areas withstanding a flood. *Complex-adaptive systems* resilience type definitions mark the opposite end of the spectrum, taking a transformative and forward-looking perspective on resilience often without providing tangible entry points for interventions. As the currently most frequently used category of resilience definition in the urban flood

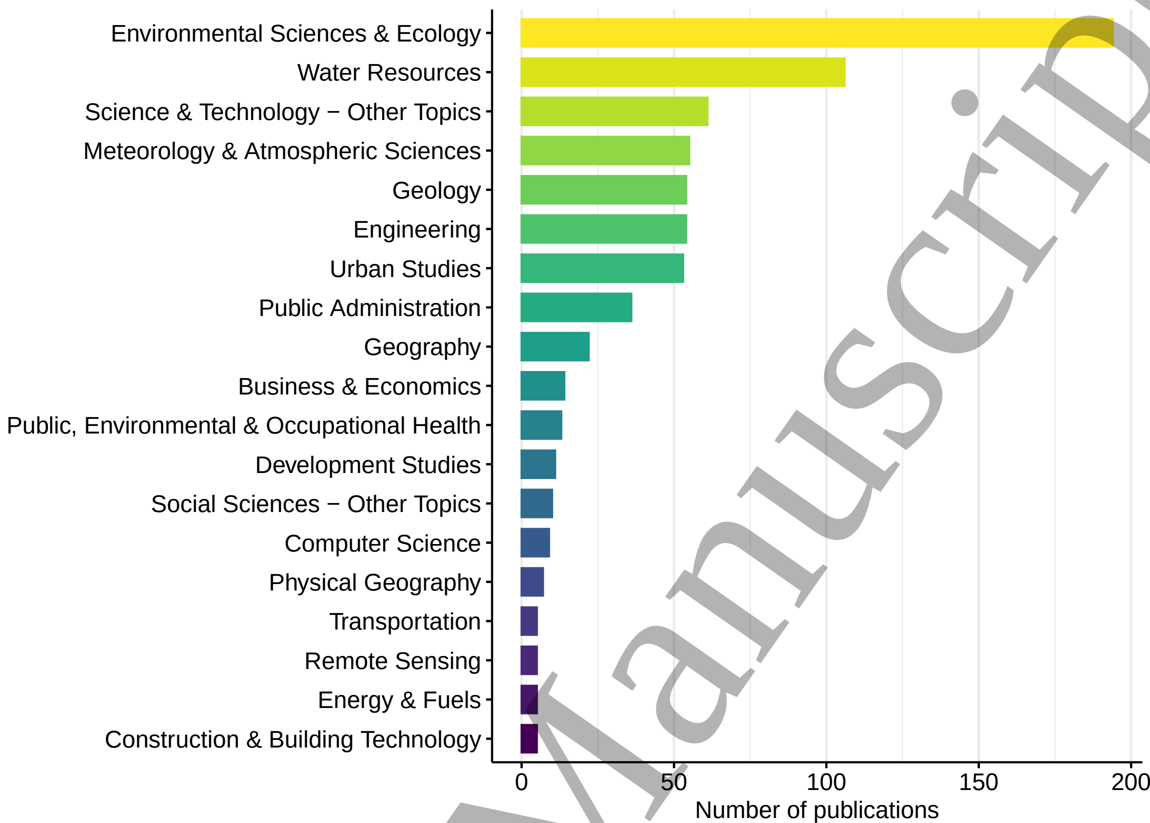

Figure 4. Number of publications by research areas as defined by Clarivate Web of Science (WoS). Of the 355 selected publications, several publications are associated with multiple research areas and have been counted once for each research area resulting in a higher total count. For publications that were only listed in the Elsevier Scopus database, the Elsevier Scopus research area naming conventions have been converted to match those of the WoS database.

resilience literature, *Systems resilience* definitions provide a more holistic understanding of resilience compared to *Engineering resilience* definitions, but are less fuzzy than *Complex-adaptive systems* resilience type definitions, which still provide a challenge when it come to translating these definitions into viable interventions (McClymont et al. 2020).

Properties and capitals of urban flood resilience: Based on the 5C and 4R frameworks described in chapter 3.2, the different dimensions of urban flood resilience covered in the literature were analysed. Figure 7A shows the share of each of the five capitals represented in the identified literature on urban flood resilience. The physical capital, which covers for example flood defences and other technical flood protection, is the most frequently considered with 90% of the reviewed publications on urban flood resilience considering this capital in their framework, assessment or analysis.Studies that are mainly focused on physical capital with little or no consideration of other capitals are often on topics related to assessing resilience of transportation systems(Duy et al.

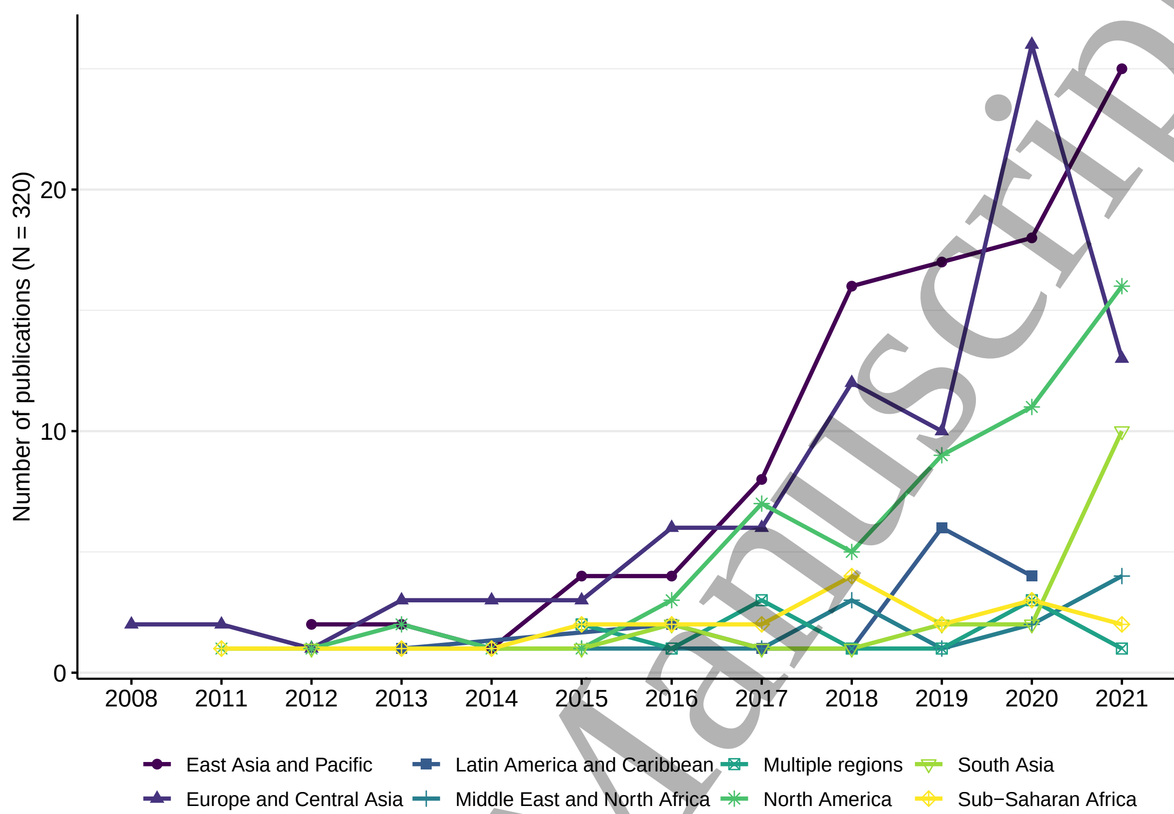

Figure 5. Geographical distribution of case studies in the reviewed literature on urban flood resilience (journal articles and other publications) by year of publication. Of the 355 selected publications, 320 contained information on case study region(s). Publications with case studies in multiple regions were classified as 'Multiple regions'.

2019, Martello et al. 2021), critical infrastructures such as drainage systems and urban supply networks (water, energy, electricity)(Karamouz et al. 2019, Wang & Palazzo 2021, Lee & Kim 2017, Yazdi 2018), or the resilience of buildings(Piątek & Wojnowska-Heciak 2020, Dewi et al. 2021). Social capital, describing the existing social networks in urban areas that underpin the resilience to flooding, is the second most frequently considered capital with 79% of the literature on urban flood resilience covering this capital. Studies with a main or exclusive focus on social capital are often related to assessing public engagement(Nirupama & Maula 2013, McEwen et al. 2018, Yusuf et al. 2018, Liu et al. 2017), communication and social networks (Vicari et al. 2019, Sitinjak et al. 2018, Yumagulova & Vertinsky 2019), as well as decision-making and governance (Rijke et al. 2013, Restemeyer et al. 2017, Dolif et al. 2013) as key dimensions of urban flood resilience. Financial, natural and human capital are each considered in less than two thirds of the publications on urban flood resilience. This highlights the strong traditional focus on technical flood protection in the literature on urban flood resilience, but interestingly there is also increasing recognition of the role of social aspects such as formal and informal social networks or societal awareness as an integrated part of flood resilience in urban areas. The grey graphs between the 5C nodes in Figure 7A represent

Table 2. Definitions of urban flood resilience and their share in the reviewed literature

Type of resilience definition	Examples	Share in the literature (N = 354)
Engineering resilience (Coping)	"In response to the increased frequency and severity of urban flooding events, flood management strategies are moving away from flood proofing towards flood resilience. The term 'flood resilience' has been applied with different definitions. In this paper, it is referred to as the **capacity to withstand adverse effects following flooding events** and the ability to quickly recover to the original system performance before the event." Chen & Leandro (2019)	12% (43)
Systems resilience (Adaptive)	"Urban resilience to floods is defined as a city's **capacity to tolerate flooding** and to reorganize should physical damage and socioeconomic disruption occur, so as to prevent deaths and injuries and maintain current socioeconomic identity. It derives from living with periodic floods as learning opportunities to prepare the city for extreme ones." Liao (2012)	70% (249)
Complex-adaptive systems (Transformative)	"Social–ecological systems and socio-technical systems are considered to behave as complex adaptive systems; they change as a result from self-organisation and external pressure de Haan (2006), Scheffer (2009). [...] The purpose of prescription for transformative governance is twofold: (1) to enable adaptive capacity for establishing resilience (i.e. to enable adaptation); and (2) to **transform existing systems into more resilient systems** (i.e. to enable transitions)."Rijke et al. (2013)	18% (62)

how often the different capitals are considered together in publications on urban flood resilience. Publications that consider physical capital together with other capitals specifically social, natural and financial capital are frequently occurring in the literature. Physical and social capital are not only the two capitals most frequently considered capitals individually, the two capitals are also most frequently considered together. This indicates a pattern in the literature on urban flood resilience, where the physical capital is used as the traditional starting point for resilience assessments or analysis and is then extended to include social, financial or natural aspects. Combinations between capitals beyond the physical capital are less frequent especially regarding a combined consideration of human and natural capital as well as human and financial capital.

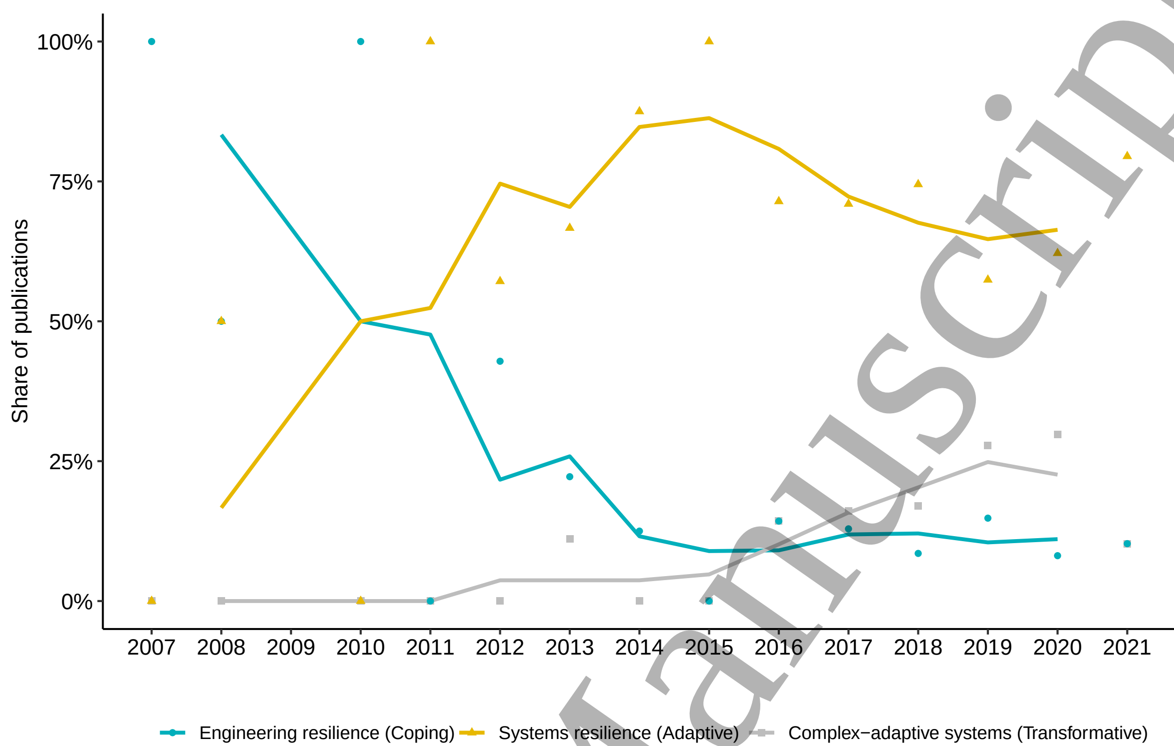

Figure 6. Share of the three different types of resilience definitions in the literature per year from 2007 to 2021. Points represent the share in a specific year, lines the moving average over 3 years. There is a noticeable decrease in the share of publications using 'Engineering resilience' definitions over the sample period with a simultaneous increase in the share of publications using first 'Systems resilience' and later 'Complex-adaptive systems resilience' definitions.

Since studies on individual capitals are often linked to specific academic disciplines (e.g. natural capital and ecology or physical capital and engineering) this indicates that silos between different fields related to urban flood resilience are still prevalent.

The 4R framework specifically looks at four key properties of resilience, described in detail in section 3.2. The reviewed literature on urban flood resilience was classified based on which of the 4Rs are considered in a publication. The results are shown in Figure 7B. Robustness describing physical strength of components such as urban infrastructure against flooding is considered in 85% of the identified literature and is closely linked to the physical capital in the 5C framework (see Figure 7A). A share of 23% of the reviewed literature focuses solely on improving robustness. These are mostly studies on improving technological solutions for flood risk management, such as improving drainage or (Guptha et al. 2021, Joyce et al. 2017) water management systems(Lerer et al. 2017, Muller 2007), green infrastructure (Ghofrani et al. 2016, Joyce et al. 2017), hazard and prediction modelling (Joyce et al. 2017), or damage assessment tools (Lee & Kim 2017). Resourcefulness or the ability to mobilise resources before, during and after a flood, such as setting up temporary shelters, is considered in 50% of the publications on urban flood resilience. Rapidity (how quickly can an urban community return to the a pre-flood state) and redundancy (can a critical component such as water supply be easily be replaced) are each considered in around 30% of the literature. Of all 4Rs, robustness and resourcefulness are not only individually the most frequently considered properties in the literature, but also most often considered together. Resourcefulness, rapidity and redundancy are least frequently considered together, which is at least in part driven by their generally lower individual occurrence in the literature. These results again highlight the strong focus of physical aspects on resilience and their properties in the literature on urban flood resilience.

In addition, only 6% of studies reviewed (N=22) include all 4Rs and 5Cs in their analysis of urban flood resilience. All of these studies were published after 2016 and either describe the development (and application) of a holistic tool, framework or approach for assessing urban flood resilience (Wardekker et al. 2020, Karamouz & Zahmatkesh 2017, Ruan et al. 2021, Moghadas et al. 2019)or argue for a resilience based approach in the governance and decision making for urban flooding (Chan et al. 2018, Iturriza et al. 2020, Fu et al. 2020).

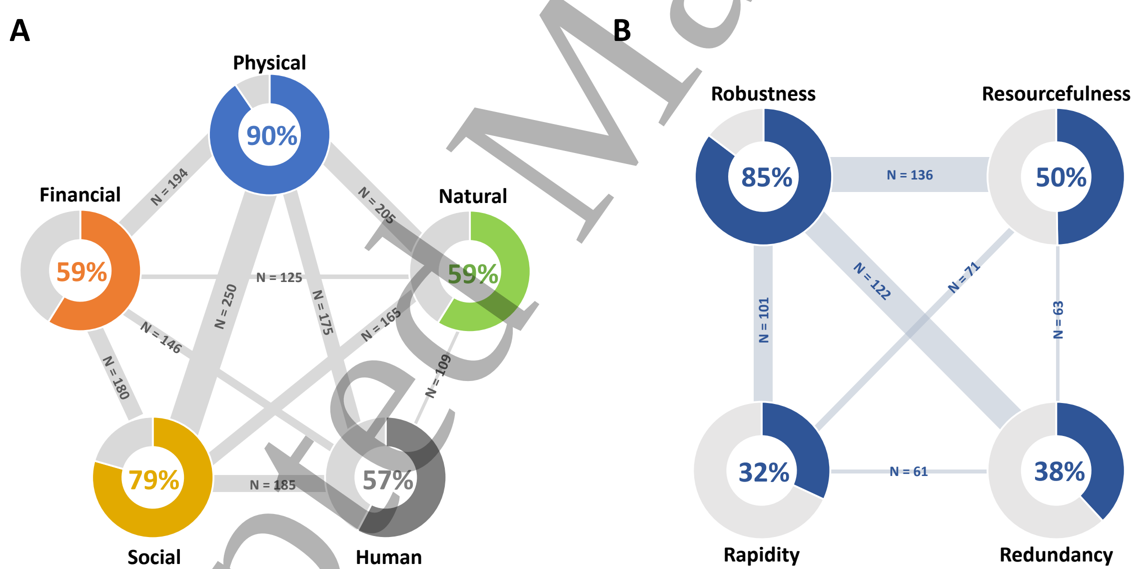

Figure 7. (A) Five capital (5C) lens of resilience: nodes represent the individual capitals and the share of the reviewed literature on urban flood resilience that consider them. Graphs show the number of publications that consider several capitals at the same time. (B) The four properties of resilient systems (4R) lens: nodes represent the individual properties and the share of the reviewed literature on urban flood resilience that consider them. Graphs show the number of publications that consider several properties at the same time.

Spatial scales of urban flood resilience: In terms of the spatial scale considered in the reviewed literature, almost three quarters of publications look at urban flood resilience on the city scale. Followed by 20% of the studies looking at urban flood resilience on the neighbourhood or urban community scale and just 6% look at the flood resilience of individual urban households (Figure 8). With the often complex interactions between different spatial scales, analysis on the city scale often include information on the neighbourhood and household scale. Multi-scale analysis on the city scale allow for a comprehensive picture on the flood resilience of an urban area including differences in resilience across different neighbourhoods and communities. Studies on individual neighbourhoods and communities mostly focus on specific contexts of these neighbourhoods based on their exposure, vulnerability or the implementation of a specific resilience increasing intervention. Studies on the household level provide an in-depth view on specific social aspects of flood resilience for example in case of marginalised urban households.

Figure 8. Distribution of the spatial scale of analysis in the literature on urban flood resilience. The percentages are calculated based on 355 reviewed publications. The publications are classified based on the largest spatial scale to avoid double counting (e.g. a publication that analyses or assesses urban flood resilience on the neighbourhood and city scale is counted as 'City'.)

4.3. Approach and challenges

Of the 355 identified publications the largest share uses either a qualitative (34%) or semi-quantitative approach (42%) when considering urban flood resilience. Around 24% use a quantitative approach of which the majority are modelling studies (20%) and only 4% of the publications are empirical studies. Over half of the identified publications describe technical assessments or measurements of urban flood resilience (56%), followed by publications on planning and strategy (23%), publications on communicating urban flood resilience (either to decision makers, the general public or practitioners) (11%) and decision support systems (4%).

In addition to the quantitative analysis of the approaches used in the reviewed literature, the reported challenges are structured and summarised qualitatively using thematic analysis. Using the approach outlined in chapter 3.3, we have surveyed the literature on urban flood resilience on commonly reported challenges until thematic saturation was reached, taking into account the different approaches and types of studies. Based on this analysis the following key themes for the reported challenges emerged: *Fairness & Equity, Climate Change, Urban planning, Data & Methods* as well as *Urban governance.*

Fairness & Equity: Environmental justice was found one of the important themes in the reviewed literature. Rapid, sometimes unplanned, urban expansion and social segregation within cities can create an unequal distribution of exposure and vulnerability to flooding. This inequality within urban areas has been addressed both as an obstacle in achieving urban flood resilience (e.g. Sajjad 2021, Rendon et al. 2021, Chelleri et al. 2015) as well as an unintended consequence in cases where flood resilience enhancing activities or measures favour more affluent individuals, urban neighbourhoods or communities and thereby exacerbating existing inequalities (see Song et al. 2019, Wang & Palazzo 2021). Restemeyer et al. (2015) conclude in their study on urban flood resilience in two neighbourhoods in Hamburg, Germany, that policy makers are often unaware of the additional added value from the co-benefits of increased flood resilience (such as attracting higher investments due to reduced risks). They therefore suggest the development of a framework that allows public authorities to support socially just and holistic approaches for private-public flood resilience projects. In their study on urban flood resilience in Badung City, Indonesia, Afriyanie et al. (2020) find a direct link between the unequal distribution of urban green spaces (favouring affluent neighbourhoods) and the increase in flood resilience using an ecosystem services framework. They further find that current zoning and land use regulations will further exacerbate an unequal spatial distribution of flood resilience across the city.

Urban planning: The challenge of increasing flood resilience in urban areas in a fair and equitable way is closely linked to urban planning. The reviewed literature highlights a lacking integration of flood resilience in urban planning as an obstacle for urban areas to become more resilient (Balaban 2016). A strong path dependency means that previous urban planning decisions can make it challenging for urban areas to become more flood resilient in the future (Bănică et al. 2020). In addition, rapid urban expansion into flood zones, especially in the global south, create new exposures and vulnerabilities to flooding, which often counteract existing efforts to increase flood resilience (Wisner 2020). Tayyab et al. (2021) suggest decision support systems for land use planning and site selection that minimise the creation of new exposure and vulnerabilities to flooding.

The proximity between different types of land-uses in urban areas can create additional health risks such as the exposure to contaminants from industrial sites or waterborne diseases from raw sewage in case of a flood (Karamouz et al. 2019). Newman et al. (2020) and others report elevated levels of pollutants during flood events often disproportionally affect disadvantaged neighbourhoods and communities (linking to the previous point on equity & fairness). This makes improving flood risk management of industrial sites an important priority in increasing flood resilience in urban areas.

Climate change adaptation: Directly connected to urban planning challenges are the impacts of climate change on urban flood resilience. Developing flood resilience strategies in urban areas under the uncertainties from climate change is challenging (e.g. Duy et al. 2019, Pandangwati 2017). The literature on urban flood resilience discuss the issue of hard limits for flood resilience particularly of grey infrastructure solutions such as urban drainage infrastructure and coastal flood defences. While they often provide good protection from flooding under current conditions they might become ineffective once their design thresholds are exceeded in a changing climate. In a study on multi-purpose flood solutions in the Netherlands, Al (2022) acknowledges that most of the current flood defence infrastructure must be seen as "temporary" as their design does not account for rising sea levels and increases in extreme rainfall. Blue-green infrastructure or nature-based solutions are discussed as alternative approaches due to their co-benefits for sustainable urban development and softer adaptation limits compared to grey infrastructure solutions (Joyce et al. 2017, Dada et al. 2021, Fu et al. 2021). The outcomes of such urban development projects are discussed in the literature under synonymously used terms such as "low impact development" in the US, "water sensitive cities" in Australia, "rainproof cities" in the Netherlands, "sustainable urban drainage" in the UK and "sponge cities" in China (Ma et al. 2020).

As one of the largest blue-green infrastructure initiatives, there is a large body of literature focusing on the outcomes and challenges of the "sponge city" concept implemented in a number of Chinese cities. The "sponge city" is a direct response to urban flood events in China where existing grey infrastructure and stormwater management has failed (Wang & Palazzo 2021, Chan et al. 2022). "Sponge cities" refer to a sustainable urban development, which combines flood control, water conservation, water quality improvement and the protection of natural eco-systems. This approach is intended to ensure an urban water system that operates like a sponge by absorbing, storing, and purifying rainwater to release it for reuse when needed (Li et al. 2017). While generally seen as an improvement compared to previous grey infrastructure approaches, the "sponge cities" concept has been criticised for not taking a holistic approach to urban flood resilience and ignoring the social needs of different local urban communities (Ma et al. 2020, Xiang et al. 2019, Chan et al. 2022).

An important challenge in developing local and context specific solutions reported in the literature, is the provision of better information on local climate change impacts. There are a number of studies suggesting ways to integrate climate change information into decision support systems for flood resilience planning in urban areas to help creating a better understanding on local climate change impacts for decision makers (Howarth et al. 2020).

Data & Methods: Following the previously mentioned studies on urban planning and decision support for climate change adaptation, one of the challenges in this context is the identification of the right indicators or metrics to assess urban flood resilience. This is in part due to the limited data availability (such as on property level protection measures) and the strong path dependency between resilience definitions and their outcomes raising the question how to best assess urban flood resilience (Forrest et al. 2020, Balica et al. 2012).

One approach described in the literature to assess flood resilience in urban areas is to rely on data-driven approaches with varying levels of complexity and demand for data (Duy et al. 2019). Another popular method for assessing flood resilience in urban areas are system modelling approaches. While these studies require less input data and therefore outputs are less determined by quality of data, they are criticised for oversimplifying the complexities and feedback loops in urban systems. In addition, many of these models are not calibrated with local information, making it difficult to rely on their outputs for decision making (Pluchinotta et al. 2021). The previously mentioned large share of qualitative and semi-quantitative studies in the literature further highlights the challenge of translating the more complex and holistic definitions of urban flood resilience into quantitative frameworks. .

Urban governance: The issue of complexity of urban flood resilience is also addressed in urban flood resilience studies with a focus on urban governance. Su (2017), Drosou et al. (2019) and others have identified the current lack of local leadership as one challenge in enhancing flood resilience in urban areas. This is often linked to conflicting goals between urban flood resilience and other development priorities including other climate related risks (Baklanov et al. 2018, Yu et al. 2020). Other studies have identified a lack of participation and local buy-in as a main obstacle to successfully increase flood resilience in urban areas.

In cases where flood resilience policies and strategies are available, it is found that those are often not or only partly implemented (Laeni et al. 2019). In a study on urban flood resilience in cities in Ghana, Cobbinah & Poku-Boansi (2018) find that the urban resilience agenda is largely defined by international organisations with little buy-in from local planners. To encourage locally driven, bottom-up approaches to increase urban flood resilience, a number of participatory approaches are suggested in the literature ranging from community driven maps for planning (Taylor et al. 2020) to apps for citizen participation (Liu et al. 2017) to multi-level stakeholder approaches (Morelli et al. 2021).

5. Discussion

Our review confirms that resilience has gained prominence in the literature on urban flood risk and disaster risk management, but our findings also agree with Restemeyer et al. (2015)'s assessment that there are still challenges in translating the concept of urban flood resilience into practice. An important issue raised by De Bruijn (2004) and Fisher (2015) is the large number of different definitions of resilience in general and for urban flood resilience in particular. McClymont et al. (2020) notes that the myriad of urban flood resilience definitions underlines the context specific nature of resilience. However, with the exception of a few publications comparing their resilience framework or concept in multiple contexts (e.g. multiple cities or neighbourhoods; see Chang et al. (2021), Duy et al. (2018), Jeuken et al. (2015)), most of the reviewed literature focuses on single case studies where the external validity of the findings remains unclear. While Hegger et al. (2016) argues that the fuzziness of urban flood resilience as a concept can be a strength as it can support a "layering" of several flood risk management systems implemented simultaneously, Cobbinah & Poku-Boansi (2018) find that the complexity and uncertainty about the external validity of the context specific findings reduce buy-in from decision makers and urban communities. Especially in cities of the global south, where resources are scarce and the vulnerable and exposed urban populations are large and growing, trade-offs between the complexity of the applied resilience framework and the practicability of its implementation need to be carefully evaluated. The disaster risk reduction literature additionally raises concerns on whether many of the proposed urban flood resilience concepts are just or whether they are misused to blame vulnerable and marginal urban communities when they fail to reduce risks they have not created in the first place (Jerolleman 2019). This is further complicated by property rights and land tenure, especially in marginalised and vulnerable urban communities. Lacking land titles and processes to establish safe development areas for new housing in urban areas create new risks and reduces the ability of communities to increase their resilience (Shi et al. 2018, McEvoy et al. 2020).

Our analysis of resilience definitions shows that while all three types of resilience definitions are used in the literature simultaneously, the number of studies using more holistic resilience definitions (systems resilience, and adaptive complex systems) has increased over time, while the share of studies using the narrower engineering resilience definitions has decreased. This dynamic evolution of urban flood resilience is important to keep in mind, as, outlined in McClymont et al. (2020), the choice of resilience definition implicitly affects both the approach and ultimately the outcome. From reviewing the literature we find that the practical implementation in urban areas is in many cases currently unable to keep pace with this conceptual evolution. We find that engineering resilience approaches predominantly focus on the physical capital (e.g., the build environment) and its robustness (i.e., withstanding a flood) (e.g. Dada et al. 2021, Lerer et al. 2017), while studies using systems or complex-adaptive resilience definitions appear more holistic and more often include social, financial, human, and environmental aspects in their analysis and outcomes (e.g. Cashman 2011, Lassa & Nugraha 2015). In combination with multiple spatial scales, we find that studies using more holistic definitions of resilience can quickly become very complex which has direct implications for their practical implementation in an urban area as it affects decisions on the data that needs to be collected and the tools that can be used. In this context several studies reported that a full implementation of their resilience framework was not possible as the data needed for that especially in regard to social, financial, and human factors could not be obtained (e.g. Barreiro et al. 2021, Ogie et al. 2018, Yang et al. 2020). This is also reflected in the small share of quantitative studies in the urban flood resilience literature, which is in conflict with the demand for quantitative evidence by decision makers (Brown et al. 2018).

Most studies in the reviewed literature focus on the development and application of new frameworks, while meta studies that allow for a like-for-like comparison of existing urban flood resilience frameworks and their outcomes are still missing. This might be due to the evolving nature of this research field. However, this can be a constraint for putting urban flood resilience into practice. We therefore argue that instead of developing ever new concepts and definitions of urban flood resilience, future studies should work towards meta-frameworks that allow for a direct comparison between the different approaches and what outcomes follow from them. This would allow to iteratively approach the two common challenges of resilience assessments highlighted by Keating et al. (2016): 1) defining the geographical and temporal scales ("resilience of what to what?") and 2) identifying the end users ("for whom?) and purposes ("for what?"). In addition, it is also important to review and compare how such resilience assessment approaches have influenced decision-making and taking actions for building resilience in different geographical and socio-economic contexts. The latter is particularly important since, as Surminski & Leck (2017) argue, there has been a great deal of effort in developing methods and approaches for assessing risk and resilience, but what often remains challenging is decision-making for what should be done when and how and the actual implementation of actions. This study has taken a structural and conceptual approach to unpack the complex, fuzzy, and multi-disciplinary aspects of 'urban flood resilience'. However, more in-depth analysis and case studies are needed to further illustrate and directly compare the various challenges identified and summarised in this study. Such a comparative approach could help to overcome a common point of criticism of resilience enhancing interventions to overemphasise one specific aspect of urban flood resilience while ignoring others (see for example criticism on Chinese "sponge cities" to overemphasise physical aspects at the expense of social and human considerations (Ma et al. 2020, Xiang et al. 2019, Chan et al. 2022)). Combined with participatory approaches as suggested by Taylor et al. (2020), Liu et al. (2017) and others, it can jointly enable decision makers and urban communities to make a conscious decision on what resilience definition and framework helps creating the outcomes they want to achieve.

6. Conclusions

In this paper, we have systematically reviewed the literature on urban flood resilience with a focus on the practical application of resilience concepts . With a focus on the application of urban flood resilience we follow suggestions from earlier studies demanding a shift from "defining" to "doing" resilience (Restemeyer et al. 2015). Starting to emerge in the 2000s, the results of our review show that urban flood resilience is a dynamic and evolving concept, initially focussing on the capacity of the built environment to cope with flooding (often referred to as engineering resilience) and now developing into complex, multi-layer, multi-dimensional frameworks including financial, human, social and environmental aspects when analysing and/or assessing flood resilience in urban areas. In relation to our first research objective (understanding the different dimensions of urban flood resilience), our review shows that this shift to a broader multi-dimensional understanding of urban flood resilience over the last decade has directly influenced the approaches taken to assess flood resilience and/or implement resilience enhancing measures, with new measures such as nature-based solutions or an increased focus on environmental justice implications in the context of urban flood resilience. Regarding our second research objective (highlighting challenges in operationalizing the urban flood resilience frameworks, tools, and approaches), we find that while progress has been made on the conceptual frontier, this development has not contributed much to closing the 'operationalisation gap'. Risks are getting more complex, and resilience interventions need to be multi-dimensional. This poses a challenge for practitioners, particularly as this also means higher demand for data (that is often not available) and difficulties in comparing outcomes between the many, nuanced approaches to assess and analyse as well as support decisions. Turning back the clock and follow the traditional narrow approach to engineering resilience would not be advisable given the scale and complexity of urban flood risk. Finally, in terms of our third research objective (identifying challenges and knowledge gaps in matching the theories and practice), we argue for a new research agenda following fields such as medicine or economics to systematically structure existing context specific findings and study designs on urban flood resilience in meta studies to ensure their comparability both in regard to the required input data and expected outcomes. This would mark a move away from urban flood resilience as a normative concept, where the choice of resilience definition determines how flood resilient an urban area is considered to be. Systematically linking resilience definitions and outcomes can help to create the evidence and deeper understanding needed by urban communities to allow them to set their own priorities when working towards an implementation of measures to become more resilient to flooding.

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Data availability

The data collected for the systematic review is available in the Supplementary Information to this manuscript.

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