Critical infrastructure and flood resilience: Cascading effects beyond water

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Abstract
Critical infrastructure and cascading effects are analyzed in this article as cross-cutting topics in flood risk and resilience. A concept is developed for integrating aspects of disaster risk, hazard, vulnerability and resilience with critical infrastructure analytic components such as redundancy, rapidity or resourcefulness. These components are expressed for each phase of an unfolding flood event and cascading effects are indicated, too. This contribution discusses the implications of such a conceptual frame for the advancement of existing flood risk management concepts. Current international guiding strategies such as the United Nations Sendai Framework for Disaster Risk Reduction, the “Making Cities Resilient” campaigns in field of urban disaster resilience, Climate Change Adaptation processes such as the Paris Agreement of the IPCC process, or urban planning in the field of UN HABITAT are all interconnected to the topic of (critical) infrastructure. The article shows how flood risk management can connect to such wider international developments by the conceptual frame discussion presented.

This article is categorized under:

- Engineering Water > Planning Water
- Science of Water > Water Extremes
- Human Water > Water Governance

KEYWORDS
critical infrastructure, disaster resilience, flood management, flood risk, flood risk management

1 | INTRODUCTION

Flood damages are one of the most prominent examples of disaster risk world-wide (Barredo, 2007; Kron, 2005; Plate, 2002) and damage to infrastructure is one of the most costly (Schulte in den Bäumen, Többen, & Lenzen, 2015; Thieken et al., 2016), yet still insufficiently studied (Merz, Kreibich, Schwarze, & Thieken, 2010). Flood resilience (De Bruijn, 2004) and (critical) infrastructure (Emanuelsson et al., 2014) are important fields of research and policy in Disaster Risk Reduction (United Nations, 2015) or climate change risk assessments (Dawson et al., 2018) but still, many components of disaster risk are not integrated yet (Di Baldassarre, Kemerink, Kooy, & Brandimarte, 2014). Already in the seminal work on flood risk and the influence of human actions to aggravate flood risk by Gilbert White it had been observed that flood damages (in the United States) kept mounting between 1920s and 1940s, despite better infrastructure and flood protection investments (White, 1945). White's work also made
aware of the “levee effect,” observing that new and better flood protection offered incentives for building property behind the new levees. However, higher river floods that overtopped these levees would take new residents by surprise; thus paradoxically increasing flood risk. The relationship between flood risk, protection, economic development and human behavior had been made quite early on, yet still the interaction of knowing about disaster and knowledge-based behavior is still one of the greatest problems in research (Weichselgartner & Kaspersion, 2010; White, Kates, & Burton, 2001). For instance, the United Nations Sendai Framework on Disaster Risk Reduction (United Nations, 2015) names four priorities for global and local actions to be met by 2030 and the first one is “understanding disaster risk.” Critical infrastructure, a term framed in context to terror attacks in the United States (US Government, 1996) is framed more prominently in the Sendai Framework as compared to the previous Hyogo Framework (UNISDR, 2005), and specific monitoring indicators are demanded (UNISDR, 2017). But global case and data contributions are still relatively low in comparison to other, more established measures such as disaster mortality or general damage (sendaimonitor.unisdr.org). This underlines the observation that critical infrastructure is a rather new field in flood risk management, as is resilience, which warrants research integrating these fields.

Critical infrastructure (CI) such as energy, transport or water supply is a societal backbone (FMIG - Federal Ministry of the Interior of Germany, 2009) in special demand during and after extreme river flood events (IPCC, 2012) that surmount resources of water engineers as well as emergency managers. Therefore, disaster resilience must take into consideration power and water shortages, road and bridge blockages and their so-called cascading effects (Pescaroli & Alexander, 2015) or cascading failures (Hernandez-Fajardo & Dueñas-Osorio, 2013) that hamper recovery of population, industry and many aspects of daily life. Cascading effects are important to consider, because infrastructures exist as large-scale interconnected networks, whose impacts extend beyond flood locations and even flood catchments. Building permissions and flood protection in river flood zones already face challenges regarding property ownership for CI assets, since in Germany, private companies own around 80% of CI (FMIG, 2009) or, construction of new electricity grid lines faces public protests. And while there are many programs or directives for flood hazard monitoring or even flood risk management, for example in Europe (EC, 2007; Hartmann & Driessen, 2017), specific regulations for CI are less regulatory and mandatory (European Commission, 2006; FMIG - Federal Ministry of the Interior of Germany, 2011). However, there are also major differences in river flood preparation and awareness between homeowners and renters (Steinführer & Kuhlcke, 2007; Thieken, Kreibich, Müller, & Merz, 2007). Disaster risk, vulnerability, and resilience studies analyze the reasons of different impacts of natural hazards such as floods on people, economies or ecosystems either semi-quantitatively, using for instance indicator approaches, or qualitatively, using surveys (Birkmann, 2013; Fuchs & Thaler, 2018).

Resilience has developed in context to natural hazards along different scholarly disciplines which is well documented (Alexander, 2013; Fuchs & Thaler, 2018) and also has received influences from non-academic sides such as most visible within community resilience, institutional or political resilience (Edwards, 2009). In context to flood resilience, the line of development of resilience is similar in many countries as it either follows a social-ecological systems approach originating in ecology (Holling, 1973) and reflected in conceptual frameworks within sustainability research (Turner et al., 2003) where flood as a hazard impacts different compartments or systems that interact with each other between conceptual components such as hazard, susceptibility/vulnerability and resilience and also are nested within different micro- and macro scales. This place-based system approach is also pronounced within frameworks such as one stemming from geography (Cutter, Ash, & Emrich, 2014). However, many overlaps exist with previous, very similar frameworks not naming resilience but coping or recovery capacities instead, especially within disaster risk index or vulnerability approaches originating within earthquake related research (Davidson & Shah, 1997) but expanding also to multi-risk approaches (Cardona, 2005). Development research and practice has also helped to make such concepts widely used, and also rather qualitative approaches were developed such as the vulnerability and capacity assessment (Anderson & Woodrow, 1998). A study revealed that in fact resilience is much older than the ecosystem approach and has developed in different disciplines quite differently regarding conceptual understanding and terminology (Alexander, 2013).

Flood resilience, in this line of research, must integrate aspects of vulnerability and exposure of traditional risk approaches for multiple stakeholders and property types that are interrelated with locations of CI assets. A conceptually challenging aspect is designating specific resilience traits that are different from existing vulnerability and risk approaches (Cutter et al., 2008; Manyena, 2006).

2 | CONCEPTUAL APPROACH AND METHODS

Resilience in context to flood risk is understood in this article as a range of abilities that are different to and expand the resistance or flood protection approach (Liao, 2012). While flood hazard modeling, flood protection and modeling should not be neglected and are key elements of a comprehensive integrated risk management approach (Trim, 2004), this paper will focus...
on the impact side of risk. Resilience will be understood as a conceptual measure promoting the analysis of stability and dynamics of human-environmental systems (Holling, 1973), and expanding risk management with aspects of complexity and uncertainty (Linkov et al., 2014) (Box 1).

Resilience in context to CI is understood here in the line of conceptual models and interdisciplinary common ground approaches developed in earthquake risk research (Bruneau et al., 2003). Typically, components in such concepts are often continuations of components previously used in risk concepts mostly related to a system approach, for example, the place-based approach on vulnerability (Cutter, 1996), similarly framed as a geographical approach (White, 1945), later reframed as resilience approach (Cutter et al., 2008). Resilience has been shown to be complementary to common risk approaches and concepts such as the (time line) risk curve (HS SAI—Homeland Security Studies and Analysis Institute, 2010), also often used within CI research on resilience (Bruneau et al., 2003; Chang & Shinozuka, 2004; Ouyang, Dueñas-Osorio, & Min, 2012) or, system resilience (Hosseini, Barker, & Ramirez-Marquez, 2016).

It is acknowledged that the work on CI originally stemmed from a protection and technical point of view (Bouchon, 2006; European Commission, 2008; Koski, 2011; Moteff, 2005; US Government, 1996), and still carries many aspects of what is termed “engineering resilience” that can differ or even be in conflict with biological systems, which often experience episodic rather than gradual or continuous change (Holling, 1996). However, modern approaches on CI resilience can also adopt a complex (adaptive) system perspective (Linkov et al., 2014) and episodic or non-continuous changes are symptomatic of many disasters that affect infrastructure as well as society or environment, just as well. Accordingly, this article will follow an integrative disaster risk management approach, which is also used for built-up environments (Haigh & Amaratunga, 2010) or within integrated water resources management (Agarwal et al., 2000). While there is still a debate on-going whether resilience is an umbrella term that simply replaces the word risk in risk management or whether resilience is just the counterpart of vulnerability (Cutter et al., 2008; Turner et al., 2003), we adopt a mediating perspective in this paper. Resilience can be incorporated into the traditional time line model as both an umbrella term and as the designated counterpart to vulnerability. This allows a rather descriptive analysis of resilience in all phases of the disaster and also allows it to be specifically designated into a recovery phase for modeling and more quantitative analyses (Bogardi & Fekete, 2018). There is a strong critique on a “bouncing back” understanding from the social sciences, which argue that certain social groups would not favor returning to the same (often dire when marginalized or poor) situation (Manyena, O’Brien, O’Keefe, & Rose, 2011). However, rather than a normative aspiration, it can be typical—especially for river floods—that social groups as well as ecological and technical systems return to the previous state and functionality rather than to transform and modify their basic functionality or identity. Of course, this is limited when certain thresholds or tipping-points are crossed (Gladwell, 2000), but this is already included within a holistic resilience understanding, which includes not just the bouncing back, but also bouncing forward and other stability regimes (Gunderson & Holling, 2002; Manyena et al., 2011). Many studies have sought to debate and integrate the confusing conceptual varieties of resilience and one study suggested an interdisciplinary and integrating rather pragmatic approach by narrowing main characteristics of resilience down to only four, the so-called “4Rs” of resilience; robustness, redundancy, rapidity and resourcefulness (Bruneau et al., 2003). This is not the only attempt to shorten the broad range of possible resilience components, but we have selected it, since it is more interdisciplinary than those that describe resilience components only for social groups (Edwards, 2009) or for mental toughness only (Gerber et al., 2013) for example. Moreover, it is explicitly suitable for integrating the topic of CI and has found wide application in this field (Chang & Shinozuka, 2004; Matzenberger, 2013; Palekiena, Simanaviciene, & Bruneckiene, 2015). However, after working with the 4R components for some years, we have also experienced certain problems in separating some of the components, such as robustness, from other

**BOX 1 INTEGRATION OF INFRASTRUCTURE DEPENDENCY AS A CROSS-CUTTING DOMAIN**

The provision of electricity and water services, transportation, information, coordination are major basic needs of modern societies, especially in times of severe crises or even disasters. Security services such as civil protection or emergency management are—just like water or electricity—services that society takes for granted; as long as they operate flawlessly under normal conditions. But even in the highly specialized fields of civil protection, daily emergency management such as fire fighting or medical emergencies or even humanitarian aid, awareness of the dependency on infrastructure services, yet even the interdependencies between them have been hardly integrated into existing concepts.
pre-existing concepts such as damage or vulnerability. We therefore suggest the following conceptual separation of terminology in Table 1, building up on previous conceptual work and documentation (Bogardi & Fekete, 2018).

The incorporation of CI conceptual thinking includes mainly a separation between first and second order risks or infrastructure failure chains (e.g., Rinaldi, Peerenboom, & Kelly, 2001), also named cascades, (Dueñas-Osorio & Vemuru, 2009; Pescaroli & Alexander, 2015; Vaiman et al., 2012), or knock-on effects (Emanuelsson et al., 2014) interdependencies (Ouyang, 2014; Rinaldi et al., 2001) or else. This idea of cascades overlaps with terminology used already in (flood) risk research and Table 1 integrates the idea of cascading effects into every conceptual disaster phase by referring to terms typically used already, such as “secondary hazard,” “secondary damage” or “spill-over-effect.” Other terms used here such as transformation or resilience are further defined in the sections below at the respective time phases and occurrences in Table 1.

3 | IMPLICATIONS OF THE CONCEPTUAL FRAME SHOWN AT AN EXAMPLE

The conceptual frame presented above (in Table 1) differentiates flood risk assessment according to typical disaster risk cycle phases. The following section intends to show the implications for addressing resilience in each time phase and also, the application options for integrating the topic of CI and cascading effects per time phase.

3.1 | Flood protection

Flood protection still is one of the major parts of flood risk management (Kundzewicz & Takeuchi, 1999; Plate, 2002), despite the rise of international research on the impact and vulnerability side after the United Nations Decade on Natural Disaster Reduction (Thomalla, Downing, Spanger-Siegfried, Han, & Rockström, 2006; UN, 1987), and while for a long time the limitations of protection are known (White, 1945), and other aspects of human behavior and knowledge are known as a knowledge transfer barrier in the complex setting of human adjustment to floods (White et al., 2001).

Aspects of resilience in the understanding of resilience covering all aspects of abilities and capacities to manage floods (Bogardi & Fekete, 2018) also cover the flood protection phase (Table 1). While protection is mostly about avoidance and prevention from the flood entering certain areas, it also bears some aspects of creating a flood culture and awareness and requires flood control and management (UN/ECE, 2003). Certain resilience frameworks include aspects of robustness (Bruneau et al., 2003) or exposure (Cutter et al., 2008; Turner et al., 2003) which relate well to flood protection measures. Also, resistance is a broad term and widely associated with many resilience components (Alexander, 2013).

For the topic of CI, flood protection and in fact all types of protective security or safety measures are not per se included into typical sectors of national CI, however, dams are, for example in the United States of America, where the concept of CI emerged (US Government, 1996). One of the cross-cutting hallmarks of the CI topic is the interdependency with other infrastructure (Rinaldi et al., 2001). Interdependency, according to Rinaldi et al. (2001, p. 14) is “A bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other.” There are different types or “dimensions” of interdependencies, such as physical (material outputs), cyber (information transmission), geographic (local) or logical (Rinaldi et al., 2001). In the case of flood protection, especially the interdependency on power, information and roads for access of maintenance or repair teams is notable. Cascading effects of flood protection

| Table 1 | Conceptual frame of flood management fields in a temporal sequence according to disaster phase, resilience, vulnerability and risk terminologies and indicating possible cascading effects per sequence |

| Disaster phase and risk time line terminology | Hazard | Impact depth / Vulnerability | Response | Adaptation |
| Resilience, risk and vulnerability terminology | Avoidance Preparedness/ Prevention Resistance | Robustness (susceptibility) Buffer and coping capacity | Rapidity of repair Redundancies Resourcefulness | Continuation (re)modification |
| Possible cascades | Secondary hazards (landslides, etc.) | Indirect damages, secondary damages | Spill-over effect on overall recovery | Spurs other adaptation processes |
failures are dam and dyke breaches, spill-overs and knock-on effects of several types, including secondary hazard triggering such as erosion, landslides or contamination.

### 3.2 Flood damage, impact and vulnerability

Within flood damage and impact assessment types, several research streams diverge; the traditional risk concept as a function of probability of floods and damage extent is still a predominant assessment type, and is often applied using damage curves or other models linking impact closely to the hazard parameters (Apel, Thieken, Merz, & Blöschl, 2006; Merz & Thieken, 2009). Economic damage is a major impact focus (Merz, 2006) and differentiations into direct and indirect, tangible and intangible damages and losses exist (Merz et al., 2010). Another research stream seeks to identify mitigation options to reduce disaster impacts (Maskrey, 1989) by analyzing vulnerability in addition to hazards, integrating economic with ecological, social and other dimensions (Cutter, Boruff, & Shirley, 2003; Davidson & Shah, 1997).

The interrelations with resilience are prominent especially with the vulnerability concept, with many discussions of overlaps, especially for the components of coping or other capacities (Adger, 2006; Anderson & Woodrow, 1998; Cutter et al., 2008). Resilience, in this disaster phase of damage depth or vulnerability (Table 1) can help to analyze robustness of human groups or structural objects. In the case of river floods related susceptibilities to be compensated by a certain robustness can be drowning of people, softening of wall material or else. Buffer capacities are another very much related resilience aspect and add to coping with flood impacts by withstanding floods for certain durations. Sand bags can provide preliminary buffer zones around houses or CI facilities.

CI often adds to flood damages by producing additional indirect impacts such as flooded roads or rail disabling relief aid or maintenance cars reaching flood-affected areas. In case of electricity grid installations being susceptible to floods, additional blackout areas increase the flood extent area into areas not flooded directly. Such blackouts and also other interruptions of CI due to floods or other hazards are also often named cascading effects or secondary effects and in Germany, for example, electricity shortages in hospitals (Thieken et al., 2016), interruptions of roads and rail (Keller & Atzl, 2014) trade (Schulte in den Bäumen et al., 2015) and other infrastructure have been analyzed after events such as the 2013 floods. In other countries, cascading effects can include a wide range of other secondary hazards or effects, for example, landmines washed away after floods (Bajic et al., 2015), spill-overs of sewage, chlorine gas production, cessation of power production, spread of diseases and many more (Pescaroli & Alexander, 2015).

### 3.3 Flood recovery

Disaster recovery (Berke, Kartez, & Wenger, 1993; Davis & Alexander, 2015; Phillips, 2015) but also terms such as reconstruction, rehabilitation or response describe the post-disaster phase efforts, while “building back better” is recently emphasized (Kennedy, Ashmore, Babister, & Kelman, 2008; United Nations, 2015) in order not to recreate pre-disaster conditions when they already were (structurally or socially) detrimental before the flood. Post-Disaster Needs Assessments (GFDRR, 2016; Kaufman & English, 1979) can guide this process by providing damage and loss (Jovel & Mudahar, 2010) assessments and link them to recovery strategies. Another related area, forensic disaster investigations or, analysis, rapidly documents key information about hazard and impact process (Burton, 2010; Kunz et al., 2014). Such assessments that have the goal “to probe more deeply into the complex and underlying causes of growing disaster losses” (Burton, 2010, p. 36) include critical cause analysis, meta-analysis (mostly literature analysis), longitudinal analysis and scenarios of disaster (Burton, 2010, pp. 37–39).

The recovery phase has much in common with the concept of resilience in its essence (MacAskill & Guthrie, 2016), the ability of a “bounce back” (Manyena, 2006) and returning into a relative stability phase (Gunderson & Holling, 2002). Many general resilience abilities can help to prepare for and improve this phase, but especially redundancies can help to retain certain functionalities by enabling access to alternative modes of transportation, backup emergency copies of information, power, food, water or else.

Three out of the “4R” components of resilience in a CI context (Bruneau et al., 2003) can be linked to several phases but mainly, to this disaster phase of recovery; rapidity of repair, redundancies, and resourcefulness. Rapidity being a general resilience aspect and especially useful for modeling and measurement of a return speed to functionality, Mean Time To Recover (Cao, Kumar, Lahiri, Li, & Putzolu, 2006) or else. Resourcefulness is the range of capacities available to help people and systems to retain and recover. Cascading effects are notable when secondary effects of a flood not only affected people or systems directly or indirectly, but also impair the emergency abilities and capacities, such as fire stations not being able to help since they are flooded themselves.
3.4 Flood risk adaptation and transformation

While some concepts regard adaptation as another component within the range of capacities, including coping capacities, especially Climate Change Adaptation research often has a different perspective than many Disaster Risk Reduction studies for its longer time frame perspective (Field, Barros, Stocker, & Dahe, 2012). Flood risk adaptation is about a change of mentality or risk management perspective, as denoted not only by the concept of “living with risks” (UN/ISDR - International Strategy for Disaster Reduction, 2004), but also by a structural adaptation of the built environment, including floating buildings, harbor areas or even cities (Morita, 2016). Dyke construction modernization such as multifunctional dykes (van Veenen, Voorden, & van der Zwet, 2015) or “giant sea walls” (Sagala, Lassa, Yasaditama, & Hudalah, 2013) are sometimes adaptation measures to Climate Change effects, yet rather seem to represent modernized flood protection measures.

Transformation is introduced as a major component of resilience (Chang & Shinozuka, 2004), especially within those concepts criticizing or rejecting the bounce back notion of resilience (Pelling, 2011). And while adaptation is mainly adjustment to a novel condition, transformation is about change or (re)modification of a system or society analyzed. This taps into many fields analyzing changes, for example demographic change, global change, and so forth.

CI aspects of adaptation and transformation include structural and strategic adjustments and modernisation of all CI components that range from physical and technical assets to human staff and regulations and the environment, in which the CI is located (Fekete, 2011). Cascading effects can play out differently, depending on how adaptation or transformation dynamics evolve; for example, there are intended and unintended side-effects of adapting to one hazard while neglecting another or when deciding for “no regret options” versus very sector-specific modifications (Heltberg, Siegel, & Jorgensen, 2009).

4 FRAMEWORK FOR CRITICAL INFRASTRUCTURE RESILIENCE AND CASCADING ASPECTS

The section above has outlined the specific interrelations between resilience and cascading effects with traditional risk concepts. The following section will summarize and further develop these interrelations and implications into a conceptual framework that can guide flood resilience assessments, but is not limited to floods, necessarily. While many conceptual frameworks of risk and resilience exist, the role of CI and cascading effects are not stressed very often. And while in traditional understanding, cascading effects in relation to water or rivers in sensu stricto focus on the cascade of a watercourse or fountain, CI uses the notion to emphasize the interconnection between triggering events and further secondary and tertiary effects. And while traditional FRM knows secondary effects, still the interdependency with CI is often not expressed explicitly. Moreover, in FRM often the interdependency is just viewed in one direction; the outcome of flood affecting other systems such as infrastructure, but not the other way around; which infrastructure is critical for FRM to function?

The conceptual framework (Figure 1) differentiates the systems that interact in case of a flood (or other event) and highlights key cascading types. Triggering events are displayed in blue and termed “stressor” as an umbrella term for both hazards and threats; hazards used more in context to natural hazards or NaTech hazards (Natural Hazard Triggering Technological Disasters, see e.g., Cruz, Steinberg, & Vetere-Arellano, 2006), threats used more in context to man-made violence or terror attacks (Borum, Fein, Vossekull, & Berglund, 1999). Stressor is also a term common in frameworks of stressor-response that are one of the influencing frameworks for risk and vulnerability frameworks in a sustainability context (Birkmann, 2006b). Systems affected or impacted by those stressors are displayed in gray; in a system of systems (SoSs) understanding, these systems are separated rather artificially in order to conceptually separate important inter-/dependencies between the systems, in this framework it is especially the interdependencies with CI that are different to previous risk frameworks, which often separate only the exposed system dimension’s such as social, ecological or economic system certain frameworks, for example (Birkmann, 2006a; Birkmann et al., 2013). The system components are displayed as cross-cutting and advance previous rather merely technological understandings of CI on components that are also essential part of CI such as human staff planning and maintaining it, customers and people of their services, regulations, and so forth (Fekete, 2011). Another important extension to typical risk assessments is the criticality assessment that identifies critical (= essential or most relevant) system elements and processes using conceptual components of criticality useful for multiple types of infrastructure and other risk related systems; critical quantity (volume), critical time factors (on-set speed, duration, temporality, etc.), and quality (Fekete, 2011). These criticality qualifiers (CQs) are indicated within the framework where they are important to prioritize the risk process in identifying critical thresholds and interdependencies. Examples on applying these qualifiers for CI risk assessments underline the usefulness of advancing existing risk assessments on this prioritization of criticality in order to save resources in the overall risk process by not having to analyze all possible interrelations, but only those most critical (Fekete, Tzavella,
Baumhauer, 2017). The framework also displays important interrelations where cascading effects can occur and Table 2 further displays and explains these cascading chains. On the right side of the framework, a typical risk assessment process (Davidson & Shah, 1997) is displayed, with stressor assessment, vulnerability and / or resilience assessment and their combination in the (pseudo) formula of risk as a function of those components.

Table 2 displays some key types of cascading events and their chains or paths. It is hoped that this conceptual framework can also help introduce the notion of CI interdependency and related cascading effects to fields such as disaster risk reduction (see final section) and offer a broader identification of cascading types. For example, typical hazard cascades are often captured in multi-hazard studies already (Cascade 1 type). However, failure of FRM or any other DRR system such as an Early Warning System (EWS) as triggers aggravating disaster losses are not often studied under the focus of cascading effects yet (Cascade type 2). Also, CI failure in their role of aggravating flood risk (Cascade type 3) is also not as common as other studies on flood risk exposure. Cascade type 4 is more commonly analyzed when spill-over effects of systems failing in disasters such as building collapses or oil-spills after flooding, and so forth, are often captured by damage and loss assessments. Of course, the claims made here demand for robust scientific review, but at this stage the purpose of this article is to merely

**FIGURE 1** Conceptual framework of Critical Infrastructure Resilience and Cascades (CIRCa)

| Table 2 Cascade explanations and examples |
|------------------------------------------|
| **Cascade Type** | **In Figure 1** | **Example** |
| Regular risk focus |  | Stressor → exposed system (e.g., general population) = > risk |
| Hazard cascade | Cascade 1 | River flood → landslide → exposed system |
| FRM system cascade | Cascade 2 | River flood → FRM system fails (example: dike breach) → exposed system ⇒ risk |
| CI cascade | Cascade 3 | River flood → CI fails (example: electricity) → FRM fails → exposed system ⇒ risk |
| Spill-over cascade | Cascade 4 | ... → ... → exposed system fails (example: flooded heating oil tanks) → system environment affected as well ⇒ risk |
| Snowball cascade |  | Any possible combination of cascade types mentioned above |

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develop this framework and indicate areas for further research. The examples provided above may not capture the whole breadth of possible spatial and temporal cascades, therefore Table 3 outlines a more general separation of cascading steps.

Generic cascading orders are sorted in Table 3 according to the criteria named in the CQ in Figure 1; volume, temporal and quality criteria, described in context to ci in previous studies (Fekete, 2011). Spatial boundaries or system boundaries are the first scale along which cascading effects can be described; when one power plant shuts down, triggering the next power plant to shut down, this would be an effect of one element of an electricity system forcing another same element type to shut down. The 2nd cascade would be when this shutdown crosses the system boundary of electricity production and, for example, production in an aluminum plant is forced to shut down production. The 3rd cascade would be that a blackout affects multiple other systems such as traffic lights, heating systems and so on. This notion is similar to studies separating the “asset scale” from the “network scale” (Dawson et al., 2018; Pant, Thacker, Hall, Alderson, & Barr, 2018). Whether these impacts are local or global depends very much on the context and should not be generalized; in one major city, all those infrastructures may exist within city boundary and are run by local companies, in another city and country, effects could cascade cross-national boundaries. Wastewater disruptions may first seem local, but when affected by certain unknown bacteria, could affect other systems, sectors or regions downstream. Temporal cascades are important to separate; some failures impact within seconds, others in hours or days; see previous applications of the CQs such as temporal aspects (Fekete, Lauwe, & Geier, 2012; Pant et al., 2018). While this separation is still within the same comparable, often linear scale metric, it is important to outline other temporal cascades when time-lag effects and irregular patterns occur such as a slowly disintegrating power line coating failing hours after the initial power failure, which often brings the second crash to a system just about recovering and then crashing it more severely. This case occurred in Bad Nauheim, a small German city with a specialized heart surgery hospital on a Friday afternoon (Joachim, 2013). Or, in case of a flood, when an adobe house collapses days after being flooded. The third temporal cascade type is when time even speeds up by snowballing effects of multiplying and spreading effects; a dyke breach is an example. The last cascade scale in Table 3 is the quality dimension; the quality of what the infrastructure delivers is affected when for example, drinking water is available, yet does not possess an acceptable quality (purity, or sediment load for instance). A cascading quality effect of 1st order would be when the same lack in quality, say, sediment load in piped drinking water, also affects other forms of the same infrastructure service, such as water used for cooling, fire fighting, hygiene, and so forth. Especially epidemics following floods can be an example. A 2nd order cascade would be when the same quality problem would spill over to other systems than water transportation, for example, when an epidemic also affects human staff which in turn cannot maintain other qualities of an infrastructure or systems anymore. As an example; polluted water after flooding a chemical factory, leading to an epidemic that leads to hospitals without staff. The hospital is still there as an infrastructure and can be used by people arriving, but it has lost the qualities of pure water and original staff. The final, 3rd quality cascade would be when not just an infrastructure service is affected, but when a quality is given up completely. This is hard to conceive, but as an example, a tsunami-flooded nuclear power plant could be given up, leading to a cascade effect of other countries abandoning nuclear power. The abovementioned cascade typology is a suggestion and will need further study to identify its usefulness and surplus-value over existing typologies of interdependencies or cascading effect types, however, the described cascade steps or turning points may be most important, serving as threshold information aspects.

5 | DISCUSSION OF RELATIONS BETWEEN FLOOD RESILIENCE, CRITICAL INFRASTRUCTURE AND CASCADES

While this section so far has set the explanatory background for the establishment of resilience fields of study in a general sense, It must now be discussed what specifics a flood resilience or, in line of this paper even more specifically, a Critical Infrastructure Flood Resilience (CIFR) approach should contain. CIFR continues the line of integrated flood risk management

| Scale      | 1st order cascade                                      | 2nd order cascade                                      | 3rd order cascade                                      |
|------------|--------------------------------------------------------|--------------------------------------------------------|--------------------------------------------------------|
| Spatial    | 1st cascade within element types of same system        | 2nd cascade crossing system boundary                    | 3rd cascade affecting multiple other systems            |
| Temporal   | affects at once, linear                                | time-lag effect, irregular patterns                    | snowballs and multiplies / speeds up                    |
| Quality    | same quality affected across similar elements/systems  | quality failure affects other services and their qualities | a whole value system is affected; quality is given up    |
by adopting a comprehensive system or even, SoSs approach (Ackoff, 1971). New foci can be introduced first of all by adding the field of CI to FRM; FRM measures such as sluice gates, pumps, monitoring systems, access roads, water and sewage systems all are part of the essential, hence CI elements for developing and maintaining a FRM in the first place, but become even more eminent and important, when failures of the CI occur and raise awareness about the interdependencies created by relying on certain CI. This extension of integrating CI into FRM also is in line with the shift of focus from purely hazard-oriented former flood defense to FRM that also includes vulnerability of affected people and other systems (such as CI). This focus or even, paradigm shift, can be pronounced by underlining or adding the term resilience to FRM, since resilience sets the focus not just on hazard or impact, but on functionality, recovery and dynamic development. While it is possible to simply replacing risk with resilience, we rather argue to keep both risk and resilience, since they retain their specific foci and strengths (Bogardi & Fekete, 2018). Criticality is another methodological extension of the existing risk algorithms or conceptual elements, as it pronounces identification of a relative importance, hence, setting thresholds and priorities. While such processes are also within the risk process, criticality provides more pronounced identification and prioritization methods, especially within CI research, that are currently explored to improve existing risk assessments, or, identification of priority areas for maintenance and renovation of river training and reliability assessment of water engineering infrastructure (Panenka et al., 2018). Another reason including CI concepts or thinking into FRM is the shift of focus on the impacts and their consequences, even patterns such as cascading effects; quite a number of CI studies suggest that the triggering hazard or stressor is important to analyze, however, within complex interdependent systems, certain failure paths and hence, cascading effects, are complex enough to warrant examination without being distracted by focusing on hazard specifics too much. This notion led to an expression of an even broader inclusion of different hazard and threat types than before or even within multi-hazard or multi-risk approaches; it is sometimes called all-hazard approach, where man-made and natural hazards are integrated. In the field of FRM this can provide an important expansion of FRM, which is often too much focused on traditional river floods or coastal flood types, and neglects failure and hazard triggers such as fires, oil spills, epidemics affecting staff, terror attacks or simply, flash floods. Flash floods happen to occur in regions not familiar with river-floods and CI failures such as electricity failures can also impair FRM elements. This exhibits mainly a big conceptual gap that prompts for more future research.

Of course, there are certain limitations to be cautioned; SoS approaches developed in other fields already showed up limitations of in theoretical basis, (Jackson, 1990) and certainly can always be related to limitations of modeling complexity. All-hazard models in EWSs have early to be criticized of side-lining the specifics of each individual hazard (Sorensen, 2000). Similar overarching concepts such as whole-of-government or society (Christensen & Latgeird, 2007)and all-hazard approaches therefore share a critique on any generalizing or integrating approach and therefore are justified in pointing out their limitations of glossing over individual specifics as much as an aggregated flood risk index hides the hidden specifics of each vulnerability indicator (King, 2001): However, as with the term resilience, the positive aspect should not be forgotten in pointing at gaps of previous approaches just conducting hazard or risk studies individually; forgetting other hazards or vulnerabilities, being oblivious to interdependencies between systems and demands for later cross-communication and avoidance of duplications of efforts. All in all, all-hazard and integrated approaches keep their importance in advancing existing individual and distributed approaches as much as individual approaches keep their importance.

Another shortcomings of this article, the conceptual framework is not exemplified at case studies or developed further. The main ambition was to introduce the opportunities arising from interconnecting fields formerly running rather separate such as Critical Infrastructure Protection and Disaster Risk Reduction. One such opportunity is advancing DRR on aspects of CI interdependency and, cascading effects related to such interdependencies. But also CI can be advanced by broadening its scope beyond mere technical infrastructure elements and their interrelations, but stressing out also how CI can be better embedded with its customers, in the case of DRR, the people affected by disaster and their situation worsened when CI also fail to support their daily needs as well as specific DRR measures such as flood response or FRM.

### 6 RELEVANCE AND WIDER APPLICABILITY OF THE PROPOSED FRAMEWORK

This interdisciplinary approach also permits integrating flood risk and resilience into wider fields of application such as global disaster risk reduction frameworks (UN/ISDR, 2005; United Nations, 2015) or urban planning. For example, UN HABITAT (UN/HABITAT, 2016) fosters an inclusive approach where basic infrastructure services are integrated into urban planning, and the resilient cities campaign (UNISDR, 2012) fosters the integration of different disaster risks with Climate Change Adaptation (IPCC, 2012), as in the Paris agreement (Hulme, 2016) and the sustainability concept (Brundtland, 1987). Urban resilience is a growing field of interest in research (Coaffee & Lee, 2016; Johnson & Blackburn, 2014), expanding currently to
advance beyond a mere focus on megacity research (Birkmann, Welle, Solecki, Lwasa, & Garschagen, 2016). But conceptual bridges between urban disaster resilience and CI are still rare and operationalization of these concepts at case studies is still a demand (Fekete & Fiedrich, 2018). Specific regulations for CI are rare in connection to river-flood risks. Flood resilience must therefore integrate aspects of vulnerability and exposure of traditional risk approaches for multiple stakeholders and locations. CI failure or damage exposure zones are harder to define spatially than existing flood exposure zones, but add a cascading effect to flood damage zones. A conceptually challenging aspect is designating specific resilience traits that are different from existing vulnerability and risk approaches. The conceptual frame presented here can indicate the specific research foci for different flood risk management paradigms or disaster phases. Concluding, while the paradigm shift from flood protection or response to flood risk management already is an on-going challenge to researchers and practitioners (Hartmann & Driessen, 2017), resilience adds another conceptual advancement, as does CI as a field currently in its infancy in being integrated into existing disaster risk reduction concepts. Beyond water—flood risk and resilience management and governance must integrate CI more into its existing concepts, since spill-overs from floods such as secondary hazards, secondary or cascading effects can aggravate the damages and impacts, by triggering blackouts, road blockages or other interruptions way beyond the water perimeter or flood zone.

**CONFLICT OF INTEREST**

The author has declared no conflicts of interest for this article.

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