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OPINION

Evolutionary leap in large-scale flood risk assessment needed

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Current approaches for assessing large-scale flood risks contravene the fundamental principles of the flood risk system functioning because they largely ignore basic interactions and feedbacks between atmosphere, catchments, river-floodplain systems, and socioeconomic processes. As a consequence, risk analyses are uncertain and might be biased. However, reliable risk estimates are required for prioritizing national investments in flood risk mitigation or for appraisal and management of insurance portfolios. We review several examples of process interactions and highlight their importance in shaping spatiotemporal risk patterns. We call for a fundamental redesign of the approaches used for large-scale flood risk assessment. They need to be capable to form a basis for large-scale flood risk management and insurance policies worldwide facing the challenge of increasing risks due to climate and global change. In particular, implementation of the European Flood Directive needs to be adjusted for the next round of flood risk mapping and development of flood risk management plans focusing on methods accounting for more process interactions in flood risk systems.

This article is categorized under:

Science of Water > Water Extremes

Science of Water > Hydrological Processes

Engineering Water > Planning Water

1 | INTRODUCTION

European and worldwide damage from floods has dramatically increased during recent decades (Barredo, 2009; Neumayer & Barthel, 2011), particularly in low and middle-income countries (UNISDR, 2015), and is expected to increase in the future due to anthropogenic climate change (Hirabayashi et al., 2013) and increasing exposure (Jongman, Ward, & Aerts, 2012). At the same time, vulnerability seems to decrease globally (Jongman et al., 2015; Mechler & Bouwer, 2015; Tanoue, Hirabayashi, & Ikeuchi, 2016), and many examples of regional adaptation appear to be a key to restrain the growing losses (Kreibich et al., 2017). To address flood threat in Europe, the European Flood Directive (EU FD; Directive 2007/60/EC, 2007) required the Member States to perform flood risk assessment and mapping, and to draft flood risk management plans (FRMPs). We argue, however, that EU Member States have failed to perform comprehensive assessments of large-scale flood risks due to immature methodologies and limited spatiotemporal scope of the analyses undertaken. This precludes an effective enforcement of the solidarity principle anchored in the EU FD, which calls for consideration of the potential adverse consequences of risk management interventions for upstream and downstream countries or communities. Furthermore, poorly quantified risks constitute a weak basis for developing adaptation strategies in the face of climatic and global changes. The lack of spatially consistent large-scale flood risk assessments is not only a deficit in Europe, but also worldwide. In the United States, for example, despite tremendous efforts in mapping local-scale flood hazard under the National Flood Insurance Program, the large-scale flood risk remains concealed (Box 1).

BOX 1

DEFINITION OF RISK

Flood risk results from the interactions of flood hazard, exposure and vulnerability (IPCC, 2012) and is characterized by the exceedance probability of certain damage over a period of time. Under flood hazard we understand the exceedance probability of potentially damaging floods in a certain area and within a specific time period. Floods are characterized by intensity indicators, such as discharge at a certain gauge or spatial inundation extent and depth. Exposure is described by the number of people and objects or asset values that could potentially be affected by floods. Finally, vulnerability is the susceptibility or predisposition of exposed elements to be adversely affected by floods.

The EU FD calls for an iterative process of assessing and mapping flood risk, and for developing, updating, and implementing FRMPs at the level of river basins every 6 years. The first round of drafting FRMPs in European countries was completed by the end of 2015 following flood hazard and risk mapping which was finalized in December 2013. However, current practice in flood risk assessment does not consider the full complexity of flood risk systems. The prevailing approach of assembling local-scale flood hazard and risk assessments into a large-scale picture ignores fundamental spatiotemporal dependencies. A multitude of interactions and feedbacks must be addressed to quantify comprehensively the upstream and downstream implications as well as indirect effects of technical measures and policy options. This complexity emerges particularly when assessing flood risk at river basin scales rather than for single reaches. Moreover, the evolution of drivers of flood risk over time needs to be traced to obtain realistic risk estimates over long periods. This is essential to assess the sustainability of flood risk management strategies, for example, to assess cost–benefit ratios for large investments like levee and retention basin construction.

It is now the time to substantially improve the current state of risk assessment approaches and invest in more scientifically credible methods before the next round of risk assessments and FRMPs. Researchers should concentrate their efforts on developing and implementing distinctively new approaches which include the complex interactions and feedbacks in and between the atmosphere-catchment, river-levee-floodplain and socio-economic domains of flood risk systems. These interactions vastly modify flood risk and may lead to profoundly different mitigation/adaptation measures and policies. Methods considering all relevant interactions in flood risk systems would constitute an evolutionary leap in the assessment of large-scale flood risks.

2 | ASSESSING FLOOD RISK—A JOURNEY THROUGH INTERACTIONS

Current methods for large-scale risk assessment seldom go beyond a simple assembly of local-scale flood extent/depths maps and damage and fatality calculations assuming certain spatially homogeneous return periods of floods (Feyen, Dankers, Bódis, Salamon, & Barredo, 2012; Rhine Atlas, 2015; Ward et al., 2013). This approach of merging local-scale maps into a large-scale picture contravenes basic atmosphere–catchment interactions, as well as interactions between upstream and downstream areas, and does not provide insight into possible flood extents or consequences related to single extreme events. Ignoring timing and synchronicity issues in flood generation may lead to significant deviations of risk estimates from actual values (Falter et al., 2015; Jongman et al., 2014). For instance, the probability of a single storm event resulting in a flood with a 100-year return period discharge peaks at all gauges in a large-scale basin is far below 0.01. Hence, a typical assumption of a homogenous flood return period over large areas will overestimate the real flood risk. Furthermore, temporal sequencing of storms and their interactions with catchment properties result in increased and spatially varying soil moisture, which can be a decisive factor for large trans-basin floods as occurred, for example, during the 2013 event in Central Europe

(Schröter, Kunz, Elmer, Mühr, & Merz, 2015). These effects remain vastly unconsidered in most of the current methodological approaches.

A few recent approaches attempt to consider some of these spatiotemporal dependencies (Jongman et al., 2014; Lamb et al., 2010; Wyncoll & Gouldby, 2015), but at the cost of methodical simplifications. For example, they focus on the spatial dependence of gauge peak flows rather than of precipitation. In that way consistent flood event sets are generated with multi-site multivariate statistical models considering spatial correlation structure of discharge peaks. If flood inundation areas are to be estimated by unsteady hydraulic simulations, this requires assumptions about the flood hydrographs at various locations. These hydrographs would, however, be not consistent with each other along the river network since they are derived from statistical considerations and not based on physical routing. Thus, risk analysis based solely on peak flows, though considering their spatial dependence, inevitably violates the water mass conservation in the river network. Hence, consistent routing is only possible for single river reaches down to major confluences or next gauges, where a new boundary, that is, another hydrograph, is defined. This precludes an assessment of upstream/downstream effects of, for example, levee failures or flood retention measures beyond single river reaches. To assess these effects unsteady hydrodynamic simulations along the entire river network are necessary.

Most current risk assessment methodologies do not account for river–levee–floodplain interactions at large scales such as load relief due to levee failures (De Bruijn, Diermanse, & Beckers, 2014; Vorogushyn, Lindenschmidt, Kreibich, Apel, & Merz, 2012). This impedes a realistic assessment of potential downstream effects of structural flood risk reduction measures. The solidarity principle set out in the EU FD requires that communities should not be adversely affected by risk reduction measures implemented elsewhere. However, the extreme flood in 2013 in Germany indicated a shift in direct economic losses towards downstream communities along the Elbe River compared to the 2002 flood event (Figure 1). This circumstance fuelled an extensive public debate into whether the large investment into structural flood defenses in the federal state of Saxony after the 2002 flood had negatively affected flood risk downstream in the state of Saxony-Anhalt (Thieken et al., 2016). After the 2002 flood, Saxony envisaged an investment of more than €800 million in structural flood defense by 2013 (Müller, 2010). The reinforced levees in Saxony largely withstood the hydraulic load in 2013, routing high flows downstream to Saxony-Anhalt, where more levee failures occurred in 2013 compared to 2002. The debate ran against the background of different flood generation characteristics of these events because, although the events are comparable in terms of overall severity, the spatial distribution of flood magnitudes was different (Figure 1). Hence, the underlying causes of the spatial shift in losses are not easily traced. This case demonstrates our feebleness in resolving such disputes, where multiple risk management actors are intertwined in a complex web of process interactions.

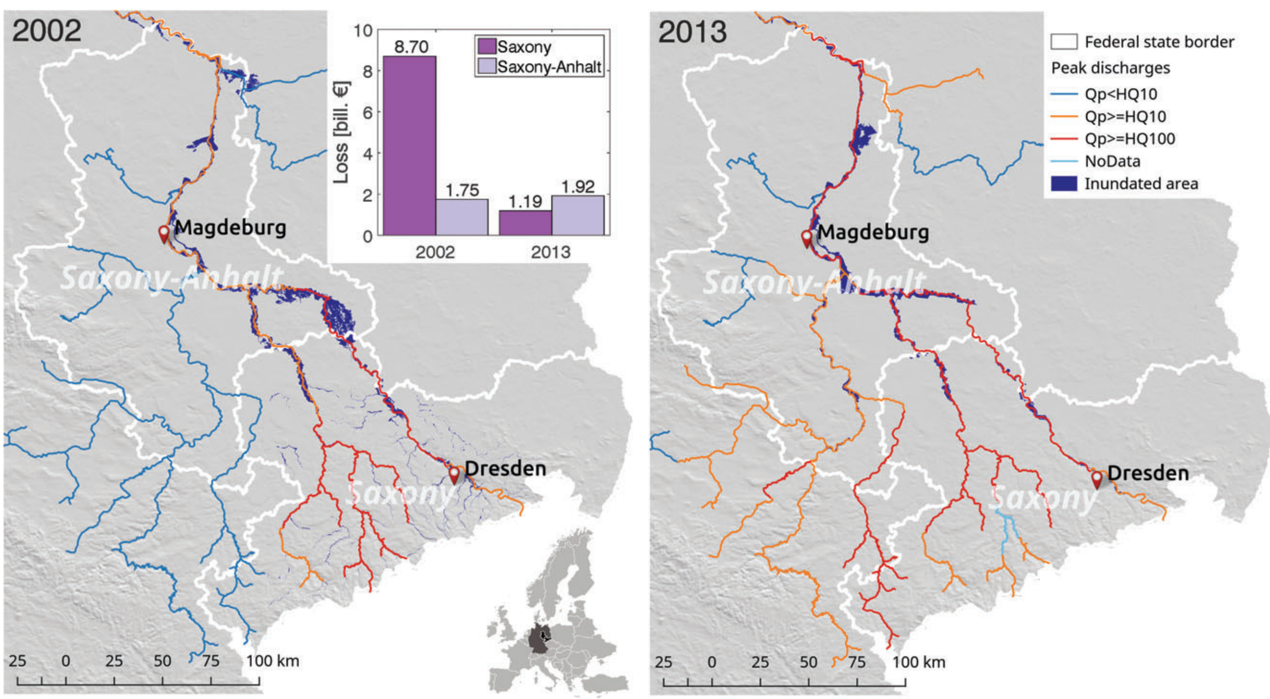

FIGURE 1 Difference in inundation areas and peak flow return periods (Qp) in the Elbe river network between the flood events in August 2002 and June 2013. HQ10 and HQ100 stand for 10-years and 100-years return period flow. The downstream shift in flood losses between the federal states of Saxony and Saxony-Anhalt is demonstrated in the bar chart. Flood loss data for 2002 and 2013 flood is taken from Pfurtscheller and Thieken (2013) and Thieken et al. (2016), respectively

Moreover, risk reduction measures such as flood detention basins may in certain circumstances result in increasing likelihood of levee failures/overflow downstream (Vorogushyn et al., 2012), which appear counterintuitive, but results from complex interactions in the river-levee-floodplain system. Due to capping of flood wave peaks by detention basins, levee failures directly downstream of detention basins can be prevented. However, this results in prolonged high water levels further downstream than would otherwise have occurred if these levees would have failed and resulted in more significant flow reduction. As a consequence, the likelihood of levee failures further downstream due to other failure mechanisms like piping may increase (Vorogushyn et al., 2012).

Risk propagation is not limited to a river basin. Increasing inter-sectoral dependence is a growing threat, which became pronounced during the Thailand flood in 2011. This long-duration event caused a substantial interruption of the production chains in the automotive and electronic industries far beyond Thailand's borders causing unexpectedly high economic losses worldwide (Haraguchi & Lall, 2015). This domino effect was a surprise also for the insurance industry, whose risk models omitted the temporal dynamics of worldwide supply chains (Merz, Vorogushyn, Lall, Viglione, & Blöschl, 2015). Novel methods are required to address the propagation of flood risk, considering indirect and systemic impacts beyond direct impacts. The first steps in this direction have been recently presented in flood impact research literature (Koks, Bočkarjova, de Moel, & Aerts, 2015; Koks & Thissen, 2016).

Besides spatial risk propagation, contemporary risk assessment approaches also largely ignore temporal changes in risk arising from alterations in vulnerability and specific local changes in exposure, for instance due to the so-called "levee effect." Many floodplains worldwide witnessed a gradual co-evolution of human settlements, flood control measures and flood hydrology (Castellarin, Di Baldassarre, & Brath, 2011; Pinter, 2005). Building flood defense systems leads to less frequent inundation, loss of collective memory and increasing value accumulation on protected floodplains over time (Di Baldassarre, Kooy, Kemerink, & Brandimarte, 2013; Domeneghetti, Carisi, Castellarin, & Brath, 2015; Viglione et al., 2014), and these may significantly alter flood risk dynamics and societal resilience (Ciullo, Viglione, Castellarin, Crisci, & Di Baldassarre, 2017). The unlucky generation that is eventually hit by a severe flood may suffer dramatically. Structural measures, although effective in reducing the total expected damage, inevitably redistribute flood damage over time and concentrate losses at a smaller number of devastating floods. The final consequences of such a policy may undermine the resilience of communities and are poorly understood and quantified to date.

This brief journey through flood risk interactions highlights the importance of considering multiple feedbacks during and between floods in risk assessments. The overall impact of interactions on spatiotemporal patterns of flood risk, particularly at large scales, and the role of different risk drivers remain unexplored using current risk assessment approaches. This is partly due to our limited awareness of complex interactions ("limited mental models") leading to risk shifts and, to a large extent, due to the lack of methods ("limited scientific models") to uncover and quantify these interactions.

3 | A CALL FOR A SYSTEMS APPROACH

Flood research urgently needs an evolutionary leap in risk assessment, focusing on interactions in order to provide methods for spatially consistent, large-scale risk quantification, and its temporal evolution (De Bruijn, Mens, Buurman, Dahm, & Klijn, 2017). To overcome the limitations of our mental and scientific models we call for a comprehensive systems approach to flood risk analysis and management. The interactions of physical and societal processes, such as meteorological extremes, runoff formation processes, performance of flood protection structures, risk awareness, private actions, and governmental policies shape spatiotemporal risk patterns and should be put center stage.

In the recent past much progress has been made in improving our understanding of flood risk and developing approaches that account for some interactions within the risk systems. In particular, analytical frameworks conceptualizing the interactions between human society and water systems paved the way for systems thinking and open a new view on controls shaping flood risk and on their dynamic feedbacks (Di Baldassarre et al., 2013; Di Baldassarre, Viglione, et al., 2013; Di Baldassarre et al., 2015). For example, Di Baldassarre et al. (2015) demonstrated by using a stylized model, how, for example, the "levee effect," that is, decreasing societal memory and vulnerability due to less frequent floods in the protected floodplains, may result in extraordinary losses, when protection fails. However, not only at the interface of human and water systems dynamic interactions are of relevance for the risk system. In various knowledge domains significant developments were undertaken including, for example, spatial dependency models (Heffernan & Tawn, 2004; Keef, Tawn, & Svensson, 2009), rapid floodplain inundation models (Bates, Horritt, & Fewtrell, 2010), coupled levee breach, and hydrodynamic models (De Bruijn et al., 2014; Vorogushyn, Merz, Lindenschmidt, & Apel, 2010), multiparameter flood damage models (Schröter et al., 2014), models for indirect losses (Koks et al., 2015; Koks & Thissen, 2016). These are the dots to be connected to achieve the required leap. As mentioned above, some approaches integrate some but few process interactions (De Bruijn et al., 2014; Falter et al., 2015; Jongman et al., 2014; Lamb et al., 2010) and an acceleration in this direction is needed to undertake the leap. As recently demonstrated by Sivapalan and Blöschl (2017) the progress in understanding hydrological systems undergoes periods of stagnation, where knowledge is accumulated and followed by sudden acceleration or step changes (leaps), where sparkling ideas fuel a major progress in the field building upon accumulated knowledge. We believe, we are currently at the foot of a next step in flood risk assessment and we need to make this leap by considering the entire risk systems with all their relevant/sensitive dependencies and interactions.

We thus advocate the development of risk system interaction-aware models involving large-scale statistical dependence models for extremes (e.g., multisite, multivariate weather generators) or physically based but fast high-resolution climate models coupled to hydrological catchment models providing spatially and temporally consistent meteorological and hydrological event footprints. The latter can serve as boundary conditions for fully coupled river-levee-floodplain hydraulic and geotechnical models taking into account potential defense failures and resulting inundation and flood dynamics. The evolution of direct and indirect, tangible and intangible flood losses must be considered over long temporal scales accounting for socio-economic development, flood coping capacity and societal resilience. Comprehensive and continuous societal cost–benefit analyses enable the assessment of flood risk management strategies and their iterative adjustment (Kreibich et al., 2014). A simple cost–benefit analysis is not sufficient, but should be extended with robustness and no-regret criteria, which reflect the distribution of costs and benefits in time and space (De Bruijn et al., 2014; Kind, Botzen, & Aerts, 2017; Klijn, Kreibich, de Moel, & Penning-Rowsell, 2015). Flood risk management will need to evolve in order to benefit from this improved knowledge of system behavior and develop strategies which go beyond mosaicking local analyses into a large-scale management agenda. Social sciences will need to play an important role in bridging the gap between improved understanding of systems behavior and actual implementation of management options at community and national levels.

Recently several risk assessment approaches have emerged at large scales that have low spatial resolution and consider some process interactions. Some approaches follow a top-down avenue starting at the large scale and trying to incorporate processes and their interactions to a degree dictated by the data availability and computational constraints (Jongman et al., 2014; Winsemius, Van Beek, Jongman, Ward, & Bouwman, 2013). Others start from the detailed process description at small scales with a focus on some interactions and expand this to large spatial scales (De Bruijn et al., 2014; Falter et al., 2016). This is a good start, but both avenues need to converge to create basin-wide flood risk models capable of informing decision-making at all levels: from building a flood protection wall in a local community to prioritizing country-wide risk mitigation investments. Likely, large-scale approaches will have their limitations and will not resolve some features (e.g., small-scale flash floods), but they should be capable to reflect the effects of interactions on larger scales even if triggered by small-scale interventions into the risk system (e.g., building a reservoir or creating a redundant power supply to a critical infrastructure). Risk assessment approaches should explore the space of different interactions and the implications for risk assessment and management. Such explorative modeling can help understand what could happen, what could go wrong and what options managers have to reduce impacts in order to avoid surprises that may have dramatic consequences (Merz et al., 2015). For practical applications, process feedback simplifications are legitimate where shown to have little sensitivity in terms of resulting risk estimates through benchmark studies with more complex approaches.

Risk assessment models incorporating a multitude of processes and feedbacks are likely to become data-hungry and computationally intensive. We fully support the plea of Ward et al. (2015) for more high-resolution data on physical properties of river and floodplain systems, on flood protection standards and vulnerability to improve flood risk models, but only a leap in methodological approaches focusing on interactions will in the end leverage the full potential of these data. We believe it will remain a pendular movement between more complex methods calling for more data and computational power and more of the latter to enable more sophisticated approaches.

Increasing pressure on policymakers, exerted through regulatory bodies and cascaded down to engineering consultancies, should target interaction-aware risk assessment. This will bring flood risk management to a new level, where the effects of individual policies and risk reduction measures can be holistically assessed at large scales and in transboundary contexts and make it fit to face the global change adaptation challenge. Now is the very time to lay down the tracks in the lead-up to the next revision of hazard and risk maps and flood risk management plans due for the EU Member States in 2019 and 2021, respectively.

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CONFLICT OF INTEREST

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