Chapter 12

Dynamic Flood Risk Modelling in Human–Flood Systems

Heidi Kreibich and Nivedita Sairam

Abstract Effective flood risk management is highly relevant for advancing climate change adaptation. It needs to be based on risk modelling that considers the dynamics, complex interactions and feedbacks in human–flood systems. In this regard, we review recent advancements in understanding, quantifying and modelling changes in risk and its drivers. A challenge for integrating human behaviour in dynamic risk assessments and modelling is the combined consideration of qualitative and quantitative data. Advancements in this respect are (1) the compilation and analysis of comprehensive qualitative and quantitative data on flood risk changes in case studies following the paired event concept; (2) the integration of qualitative and quantitative data into socio-hydrological models using Bayesian inference; and (3) the coupling of hydrological flood risk models with behaviour models in socio-hydrological modelling systems. We recommend to further develop these approaches and use more such process-based, dynamic modelling also for large-scale flood risk analyses. These approaches are increasingly feasible due to significant improvements in computational power and data science.

Keywords Socio-hydrology · Stylized models · System-of-systems models · Agent-based models

Introduction

Flood risk assessment and management are highly relevant for advancing climate change adaptation, since floods cause very large amounts of material damage and casualties worldwide (Kundzewicz et al. 2014). From all natural hazards, they affected the largest number of people (>2 billion) globally in the period 1998–2017

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and they caused €52 billion in overall losses in Europe in the period 1998–2009. Due to climate change and increasing exposure, e.g. via urbanization, the risk of flooding is expected to increase in the future (Kundzewicz et al. 2014). However, data and modelling driven studies also show that effective adaptation including flood risk management has a high potential to counteract the effect of climate change (Kreibich et al. 2017; Metin et al. 2018).

There is general agreement that flood risk, as well as its components (hazard, exposure and vulnerability) are dynamic, and should be treated as such (Vorogushyn et al. 2018). Hazard is defined as the potential occurrence of an event that may cause adverse effects on social elements, while exposure is defined as the presence of people, livelihoods, environmental services and resources, infrastructure or economic, social or cultural assets in places that could be adversely affected by physical events. Vulnerability is defined generically as the propensity or predisposition to be adversely affected. Finally, impacts, e.g. direct damage such as fatalities or economic damage, represents risk. Adaptation aims to reduce the overall risk, which can be done by reducing the hazard (i.e. the frequency/magnitude of flooding, e.g. via structural protection measures such as retention basins or levees), the exposure of people and properties or their vulnerability to flooding. However, changing one of those risk components may lead to unexpected behaviour of the system as a whole, resulting in phenomena like the levee effect, i.e. the increase of exposure and vulnerability behind levees due to the non-occurrence of flooding (Di Baldassarre et al. 2018).

Due to continuous feedbacks across the human–flood system, risk-based decision-making requires understanding, quantifying and projecting changes in risk under an integrated, systems framework (Barendrecht et al. 2020; Vorogushyn et al. 2018). In this regard, this review is focused on approaches to quantify the temporal dynamics of risk and its drivers as well as to project flood risk changes in the future. It draws particularly from two preceding studies: the opinion paper ‘How to improve attribution of changes in drought and flood impacts’ (Kreibich et al. 2019) and the review paper ‘A dynamic framework for flood risk’ (Barendrecht et al. 2017). Thus, state-of-the-art empirical data-driven knowledge and modelling methods are discussed.

Empirical Data-Driven Knowledge

Aggregated flood damage data at the event level, available from several global, regional and national databases, are used for trend analyses (Bouwer 2011). However, due to the event level and large spatial scales of analyses, the studies cannot provide insights into processes (Bouwer 2011). Empirical flood risk data on the micro-scale in case studies, available from participatory studies, surveys, official statistics or open access data sources are valuable for gaining process understanding in respect to the dynamics of risk (e.g. Sairam et al. 2019). However, long-term analyses in local case studies are only rarely possible. Thus, the recently developed paired event concept is an important advancement (Kreibich et al. 2017, 2019). It consists of analysing changes in risk and its components (hazard, exposure, vulnerability) as

well as processes and interactions based on paired events in the same catchment or region, irrespective of the time between events (Kreibich et al. 2017). It is not limited to one pair of events, but the more events that are considered for the same region, the better. The paired event concept is analogous to the concept of ‘paired-catchment studies’, which is a well-established concept in hydrology (Kreibich et al. 2019).

Temporal trend analyses on flood damage data detect a clear increase in damage (Bouwer 2011). Most of these studies find that the observed increase is due to societal change and economic development. An effect on damage from changes in flood hazard due to climate change has hardly been observed until now. However, exposure and vulnerability are largely influenced by human interventions such as flood protection and their interaction and influence on risk can only be roughly accounted for over time (Bouwer 2011). Thus, it is hypothesized that an increase in flood hazard is counteracted by a decrease in vulnerability, e.g. via effective flood risk management, including protection, early warning and preparation (Jongman et al. 2015). A decrease in vulnerability seems to have occurred at the global level since about 1980, which is reflected in decreasing mortality and losses as a share of population and gross domestic product exposed to river flooding (Jongman et al. 2015). On national scale, it is reported, e.g. that in Bangladesh, vulnerability towards flooding has decreased strongly since 1974, which seems to be due to substantial improvements in flood risk management (Mechler and Bouwer 2015). An empirical analysis of eight paired event case studies around the world showed that an observed reduction in flood impacts was driven mainly by reductions in vulnerability (Fig. 12.1). Such detailed case study-based analyses revealed that vulnerability can be positively influenced by integrated flood risk management, which complements structural protection with non-structural solutions, e.g. private precaution, land-use planning and insurance (Kreibich et al. 2017). However, vulnerability can also be negatively influenced by changes in building materials, increasing dependence on critical infrastructure, or changes in business processes. For instance, recent reports by insurers emphasize that floods cause tremendous losses, particularly to modern buildings with good thermal insulation and innovative building materials. While these buildings perfectly fulfil the requirements of energy-saving standards that are important to mitigate climate change in the long run, it seems that such constructions tend to increase average building losses due to their high susceptibility to flooding (Kreibich et al. 2019). In summary, knowledge about changes in vulnerability and risk, particularly their drivers and driver interactions is scarce so that more monitoring and empirical data analyses are necessary, including new data sources such as satellite data and social media.

Modelling Changes in Flood Risk

Since data-driven knowledge is limited to inferences derived from past trends, modelling approaches are necessary for projecting future trends or developing future scenarios for flood risk. Therefore, modelling approaches that consider drivers of risk along with their interactions and feedbacks are a necessary step forward for

Fig. 12.1 Analysis of eight paired flood events showing the difference in primary drivers of change in flood risk and fatalities and economic losses between the first flood event, which serves as the baseline, and the second event (published by Kreibich et al. 2017)

adaptation. In this section, three categories of state-of-the-art socio-hydrological modelling approaches that aim to project trends in flood risk are discussed: stylized models (SYMs), system-of-systems models (SSMs) and agent-based models (ABMs) (Barendrecht et al. 2017). The implementation of these approaches is strongly influenced by the spatial scale of risk assessment, availability of expert knowledge and empirical data.

Modelling Approaches

SYMs capture system characteristics based on a set of processes, which are simplified into a set of differential equations (Viglione et al. 2014). These models are examples of a top-down approach, and are relatively straightforward to implement. They can be used to interpret the general characteristics of the system. For example, a local flood risk SYM is implemented in the city of Dresden, Germany (Barendrecht et al. 2019). This is a lumped model with simplified representations of relationship between flood experience, awareness, preparedness and damage processes. The use of Bayesian inferencing in the SYM allows hydrologists and social scientists to introduce their degree of belief in certain processes as priors. Further, this opens up the possibility to integrate empirical qualitative and quantitative data from recorded events as evidence (Barendrecht et al. 2019). In this case, data for the case study of Dresden, over a period of 200 years, were used to estimate the model parameters through Bayesian inference. As such, the inferences from the model are helpful to understand the general nature of human–flood feedbacks prevalent in the specific case study. Thus, changes in flood risk based on general system characteristics can be quantitatively estimated using process-based SYMs.

The SSMs are developed by coupling relevant detailed individual models that capture different processes within the system. These models are spatially explicit and as such capable of producing risk scenarios that are most relevant to the regional/local scale. SSMs often include assumptions regarding some components of the system and possible synthetic scenarios, as well. An example of an SSM relevant to flood risk is the regional flood model (RFM) implemented in the Elbe catchment in Germany (Falter et al. 2015; Metin et al. 2018). The advancements in the hydrology and hydraulics along with the increase in computational capabilities have enabled continuous simulation of the flood risk chain (Falter et al. 2015). This is a significant advancement in comparison to the previous simple assembly of local, static inundation maps (Metin et al. 2020). However, in comparison with the hazard component, there is a lot of scope for advancing quantification of changes in vulnerability, considering human–flood dynamics. Though this study is based on an SSM which consists of coupled well-researched hydrological, hydraulic and multivariable damage models (Fig. 12.2), synthetic adaptation scenarios define the feedbacks within the human–flood system (Falter et al. 2015).

ABMs capture the characteristics of individual components in the system (agents), their interactions and feedbacks. The overall system characteristics may be inferred based on this. This is an example of a bottom-up approach. The ABMs may be process-oriented where the behaviour of each agent is modelled based on behavioural theories such as protection motivation theory, expected utility theory or prospect theory (Haer et al. 2017). Additionally, evidence from empirical data may be used to determine the behaviour or update the model using Bayesian inferencing (Haer et al. 2017).

Fig. 12.2 Components and data requirements of the Regional Flood Model—RFM (adapted from Falter et al. 2015)

Role of Spatial Scale

Flood risk is stochastic and exhibits spatio-temporal variability with respect to damage processes (Sairam et al. 2019). It is possible for local/regional modelling studies to use vulnerability scenarios relevant to the case study. However, in the case of large-scale flood risk assessments at the continental or global scales, shared socioeconomic pathway scenarios are commonly used as vulnerability scenarios. As for instance for the implementation of an integrated ABM into a large-scale flood risk assessment model for the European Union (Haer et al. 2019). Recent studies derive global vulnerability projections based on comparing flood damage (losses and fatalities) against coarse indicators such as population and gross domestic product

of regions (Jongman et al. 2015). More effort is needed for translating micro-level human–flood interactions and feedbacks into large-scale modelling frameworks for improved decision-making.

Conclusion and Recommendation

The dynamic modelling of flood risk considering human–flood interactions is highly relevant for an effective flood risk management and as such for advancing climate change adaptation. Important recent advancements in quantifying human–flood dynamics and integrating this knowledge into dynamic flood risk modelling are the following:

Compiling and analysing qualitative and quantitative data about temporal changes in hazard, exposure, vulnerability and impacts and how these components are influenced by risk management in case studies advances our process understanding of human–flood systems. A promising approach is the paired event concept presented by Kreibich et al. (2017).

Integrating qualitative and quantitative data into socio-hydrological models supports the simulation of real, long-term processes in human–flood systems. Available empirical data from recorded events can be used to calibrate and validate the models. A promising approach is using Bayesian inferences in the modelling to integrate qualitative and quantitative data as shown by Barendrecht et al. (2019). Coupling hydrological flood risk models with behaviour models in a socio-hydrological modelling system captures the feedback processes across the human–flood systems. A promising approach is the coupling of an ABM into a flood risk modelling system, like presented by Haer et al. (2019).

Despite these advancements, current approaches for large-scale flood risk assessments still largely ignore basic interactions and feedbacks of the human–flood systems and use too coarse data and models. Thus, we recommend to develop and use more process-based modelling systems based on more detailed and comprehensive data also for large-scale flood risk analyses, which becomes more and more feasible due to significant improvements in computational power and data science.

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