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Preface: Advances in pluvial and fluvial flood forecasting and assessment and flood risk management

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The special issue "Advances in pluvial and fluvial flood forecasting and assessment and flood risk management" builds on topics covered in the session "Advances in pluvial and fluvial flood forecasting and assessment and flood risk management" organized since 2018 at the European Geosciences Union (EGU) General Assembly held in Vienna, Austria. It gathers five research papers on flood modelling and management.

Worldwide, flooding is the foremost natural hazard. It affects human life and property, directly and indirectly (e.g. IPCC, 2022; Prieto et al., 2020; Blöschl et al., 2019a; Phillips et al., 2018; Berghuijs et al., 2017; European Parliament, 2017). In the European Union and in the United Kingdom, river flooding causes annual losses of about EUR 7.6 billion and affects around 160 000 people per year (European Commission, 2023). Dottori et al. (2023) state that under a 3 °C temperature increase scenario and without adaptation, annual flood losses in Europe would rise to EUR 44 million, affecting 0.5 million of Europeans every year until the end of the century. Flooding and severe storms are among the most recurrent weather and climate disasters in the United States, causing USD 492 billion in economic damages in the past 30 years (NOAA, 2024). In developing or least developed economies, 28 million people are prone to coastal flooding due to tropical storms (Edmonds et al., 2020). Additionally, in these countries, especially in the tropics, long-term climatic fluctuations such as ENSO (El Niño–Southern Oscillation) can lead to extreme sea level events and related coastal hazards (Pelckmans et al., 2023).

Developed countries are expected to benefit from the most advanced mitigation measurements. Nonetheless, the costliest flood event over the last decade occurred in July 2021 in Germany and Belgium, with losses of EUR 44 billion (European Environmental Agency, 2023), showcasing that the whole world needs to adapt to offset the projected rise in flood risk. In 2022, floods caused the death of roughly 7400 people globally, and more than 54 million people were impacted by floods worldwide in 2022 (Burgueno, 2023). Global warming will also slow down atmospheric dynamics, resulting in more precipitation falling over a longer period, thus increasing flooding hazard (Kossin, 2018; IPCC, 2023).

Despite the many hydrological and hydrodynamic modelling techniques currently available to inform flood risk assessment and management (Prieto et al., 2021; 2022; Han, 2011; Mignot and Dewals, 2022), many open questions remain, as reflected for instance in the list of "Twenty-three Unsolved Problems in Hydrology" (Blöschl et al., 2019b) and in the programme of the HELPING decade of the International Association of Hydrological Sciences (IAHS). Two particularly timely challenges in flood risk management relate to (1) improvement of spatial predictions of urban flooding and the quantification of their uncertainties (Skougaard Kaspersen et al., 2017; Hooker et al., 2023) and (2) evaluation of the effectiveness and efficiency of non-structural measures (e.g. nature-based solutions, dam operation rules) to mitigate flood hazard (Guido et al., 2023; Pelckmans et al., 2023; Férnandez-Nóvoa et al., 2024). The papers in this special issue contribute to addressing these two challenges, as outlined in the next sections.

1 Challenge 1: improvement of spatial predictions of urban floods and quantification of their uncertainties

Societies face fast-growing urbanization and city development, which increase the frequency, severity, and impact of extreme events (Skougaard Kaspersen et al., 2017). Predicting flood extent and flow depth in urban pluvial flooding is a major scientific and practical challenge. Two-dimensional hydrodynamic models (Abebe et al., 2019; De Almeida et al., 2016) are nowadays complemented by data-driven approaches for flood hazard mapping (Costabile et al., 2017; Guo et al., 2022). The latter are comparatively less demanding in computational resources. Data-driven models are known to perform well in domains in which they have been trained, while a remaining challenge is how to transfer such models beyond their training domain (e.g. Kratzert et al., 2019). In this special issue, Seleem et al. (2023) investigate the transferability of data-driven models, particularly convolutional neural network (CNN) and random forest (RF), to emulate a 2D hydrodynamic model (TELEMAC-2D) in three neighbourhoods in Berlin. The data-driven models were trained to map topography, land cover, and precipitation variables to observed flood water depths. The depth of a depression was found to be the most influential predictive feature, for both CNN and RF. The models' performance was assessed by comparing the water depths and inundation extents predicted by the data-driven models against TELEMAC-2D outcomes. The authors found that CNN performed better than RF in generalizing beyond the training domain and benefiting from transfer learning. The study highlights the importance of collecting extensive training and testing datasets, as well as the potential offered by data-driven methods for flood hazard mapping in urban environments.

Uncertainty quantification of flood mapping is instrumental to allow stakeholders to take informed decisions (e.g. Prieto et al. 2021, 2022). Unlike deterministic flood hazard maps (Arnal et al., 2020), the uncertainty in the flood predictions can be represented by an ensemble of forecasted inundation maps, providing a location-specific likelihood of flooding (e.g. Cloke and Pappenberger, 2009). In this special issue, Hooker et al. (2023) present a novel approach to assess the spatial predictability and spread skill of ensemble flood mapping based on historical flood events. The method computes two metrics: (i) the ensemble spatial spread is the agreement between every unique ensemble member pair of floods map at each grid cell, and (ii) the ensemble spatial skill is the agreement between each ensemble flood map and each ensemble flood map derived from a synthetic aperture radar (SAR). The difference between (i) and (ii) can be mapped into a so-called spatial spread skill (SSS) map. The SSS map shows whether the ensemble is over-spread, under-spread, or well-spread for each location. The methodology is showcased for the August 2017 flood on the Brahmaputra River in the Assam region of India. Spatial variations in spread skill can be linked to the physical characteristics of the flood event.

2 Challenge 2: flood mitigation using non-structural measures

Nowadays, flood risk management increasingly relies on measures which do not involve the construction of grey infrastructures. In this move, nature-based solutions (NBSs) have gained popularity, given their capacity to enhance flood resilience while delivering side benefits. The International Union for Conservation of Nature (IUCN, 2022), the World Bank Group, and the World Resources Institute (WRI) define NBSs as "actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, 2022). Therefore, NBSs are often regarded as low- or no-regret options that provide benefits for both people and the environment (Faivre et al., 2017; European Commission, 2024). Examples of NBSs are reforestation and afforestation, wetland restoration, and sustainable land management practices which reduce runoff. Although NBSs have proved effective in reducing and/or delaying flood peaks and volumes in urban or coastal areas, they are still not mainstream due to limited knowledge and testing compared to more traditional engineering solutions. A current key challenge is how to incorporate NBSs into hydrological and hydrodynamic models.

In this issue, Guido et al. (2023) propose an integrated methodology for selecting, modelling, and evaluating the performance of NBSs to alleviate hurricane-driven floods. Flooding induced by Hurricane Matthew in the United States was used as a case study. Guido et al (2023) applied the hydrological model HEC-HMS and the hydrodynamic model HEC-RAS to identify the optimal positioning of NBSs in a catchment. Three types of NBSs were considered (flood storage ponds, riparian reforestation, and afforestation in cropland). Afforestation in croplands leads to the most substantial reductions in flood discharge and inundation extent. This result is attributed to the larger scale at which this measure operates compared to flood storage ponds and riparian reforestation. Importantly, the study by Guido et al. (2023) indicates that identifying optimal NBSs is case-dependent and that several scientific questions remain unanswered (e.g. effect of low-intensity storms, steeper slopes).

Current knowledge on how mangroves can attenuate high water levels in large-scale deltas is restricted to modelling studies, which did not capture the complex geometry of channels intertwined with intertidal wetlands, or small-scale studies, which only quantified attenuation inside mangroves. In this special issue, Pelckmans et al. (2023) present a delta-scale hydrodynamic model, accounting for complex landforms, for the case of the Guayas River delta (Ecuador), which is the largest estuarine system on the Pacific coast in Latin America. The authors used water depth measurements in the mangroves to calibrate the mangrove platform elevation. Despite limited data availability, the delta-scale model captured the propagation of high water levels during a spring tide. The authors make the following key contributions: (i) mangrove elevation and the presence or absence of mangroves is more important than mangrove-induced drag (and hence mangrove vegetation properties) in determining high water levels across the delta; (ii) the elevation of intertidal flats, located near the downstream end of the delta, has less effect on along-channel attenuation than upstream-located wetlands; and (iii) the degree of channelization inside the mangrove forests determines high water levels both upstream and downstream. Therefore, mangroves with a lower surface elevation, lower vegetation density, and higher degree of channelization favour attenuation of high water levels in the deltaic channels. Future research could apply the methodology proposed by Pelckmans et al. (2023) in combination with freely accessible global remote sensing data to cover a wide variety of river deltas and evaluate the potential of conserving wetlands as NBSs for reducing flooding in river deltas.

Another non-structural flood mitigation measure (WMO, 2011) consists of adapting existing dams' operation rules. Fernández-Nóvoa et al. (2024) present a strategy to take advantage of several large dams and reservoirs located along the Tagus River (Portugal) to effectively mitigate a record flood (February 1979). This event is analysed based on a validated hydrodynamic model, with a focus on the multipurpose reservoir of Alcántara, which contributes to water supply and hydropower in addition to flood control. Results indicate that the proposed strategy allows diminishing the number of days under flood conditions by more than 80 % with respect to a natural regime (i.e. without dam). The proposed operating strategy is especially effective in reducing water depth and water velocity in the flooded areas (∼ 25 %–30 %), which is critical for reducing flood damage. A smaller reduction in flood extent was achieved (∼ 5 %–10 %). The study used open data (e.g. Copernicus DEM) and free modelling software. The Fernández-Nóvoa et al. (2024) study can be viewed as a step towards improving knowledge on extreme floods in the lower Tagus valley and towards providing strategies to mitigate these events. It takes advantage of existing infrastructures, thus addressing one of the most important challenges that the scientific community will face in the coming decades as a consequence of increasing precipitation due to climate change, particularly in the Iberian Peninsula (IPCC, 2023).

3 Conclusion

Each paper in this special issue addresses one or several aspects of these research challenges: (i) improvement of spatial flood predictions and quantification of their uncertainty (Challenge 1) and (ii) enhancement of knowledge on flood mitigation based on non-structural measures, including nature-based solutions (Challenge 2).

Regarding Challenge 1, Seleem et al. (2023) show how more reliable and accurate spatial flood predictions can be achieved when transferring data-driven urban flood models beyond their training domain, while Hooker et al. (2023) contributed to evaluating the quality of uncertainty predictions in ensembles of forecasted flood maps.

In line with Challenge 2, Guido et al. (2023) showcase a simulation-based integrated methodology for the optimal design and positioning of NBSs to mitigate hurricane-induced flood hazard. In the context of assessing the effectiveness of mangroves at attenuating the propagation of extreme sea levels through large (order of 100 km^2) estuarine or deltaic systems, with complex geometry formed by networks of branching channels intertwined with mangrove and intertidal flat areas, Pelckmans et al. (2023) showed that the wide range of observed and modelled attenuation rates can be partly explained by variations in the wetland platform elevation and degree of channelization, in addition to vegetation properties. Using a validated hydrodynamic model of a case study in Portugal, Fernández-Nóvoa et al. (2024) present a strategy to adapt the operating rules of existing infrastructure, namely multipurpose dams and reservoirs, to mitigate extreme floods, achieving a reduction in flooded areas of up to 30 %.

The five papers in this special issue collectively highlight the need for further research beyond the two challenges discussed here. They specifically point at research avenues such as (i) further exploring the use of artificial intelligence for flood predictions and particularly the transferability of such models, as well as the associated uncertainties, and (ii) creating databases and catalogues of case studies of NBS implementations (covering both successes and failures) to progress towards a better appraisal of their effectiveness in a broad range of contexts.

Looking ahead, the 2030 Agenda for Sustainable Development places great emphasis on flood risk reduction and the interaction between flood and poverty, availability of flood, access to healthcare, water supply, infrastructure, urban development, adaptation to climate change, and the preservation of ecosystems. The 2030 Agenda for Sustainable Development highlights the urgent need to reduce flood risks. Indeed, a major disaster can wipe out the economic and social progress that a country has taken years to achieve (Bello et al., 2021). In order to achieve the "Sustainable Development Goals" by 2030, in particular Goal 6 ("safe water and sanitation for all"), and to move towards successful flood risk management and planning, we need to continue research and take rapid action to improve flood forecasting (e.g. flash floods) and impact-based forecasting, reduce vulnerability and exposure, and adapt mitigation strategies that include NBSs (e.g. by adapting urban planning to incorporate a combination of NBSs and other measures in a holistic way).

Data availability. This special issue is a compilation of published papers that summarize contemporaneous aspects in "Advances in pluvial and fluvial flood forecasting and assessment and flood risk management". The data can be found in each individual paper.

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