

1 **ADVANCES IN PLUVIAL AND FLUVIAL FLOOD FORECASTING, ASSESSMENT, AND RISK MANAGEMENT**

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14 **1. Introduction**

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

19 Worldwide, flooding is the foremost natural hazard. It affects human life and property, directly and indirectly
20 (e.g. IPCC, 2022; Prieto et al., 2020; Berghuijs et al., 2017; European Parliament, 2017; Blöschl et al. 2019a;
21 Philips et al. 2018). In the European Union and in UK, river flooding causes annual losses of about EUR 7.6
22 billion and affects around 160,000 people per year. Dottori et al (2023) state that under a 3°C temperature
23 increase scenario and without adaptation, annual flood losses in Europe would rise to EUR 44M, affecting
24 0.5M of Europeans every year until the end of the century. In the United States, flooding and severe storms
25 are also among the most recurrent weather and climate disasters. They have caused USD 492 billion in
26 economic damages in the past 30 years (NOAA, 2024). In developing or least developed economies, 28 million
27 people are prone to coastal flooding due to tropical storms. Additionally, in these countries, especially in the
28 tropics, long-term climatic fluctuations such as ENSO (El Niño–Southern Oscillation) can lead to extreme sea
29 level events and related coastal hazards (Pelckmans et al 2023).

30 Developed countries are expected to benefit from the most advanced mitigation measurements.
31 Nonetheless, the costliest flood event over the last decade occurred in July 2021 in Germany and Belgium,
32 with losses of EUR 44 billion (European Environmental Agency, 2023), showcasing that the whole globe needs
33 to adapt to offset the projected rise in flood risk. In 2022, floods caused the death of roughly 7,400 people
34 globally and more than 54 million people were impacted by floods worldwide in 2022 (Burgueño, 2023).
35 Global warming will also slow down atmospheric dynamics, resulting in more precipitation falling over a
36 longer period, thus increasing flooding hazard (Kossin, 2018, IPCC 2023).

37 Despite the many hydrological and hydrodynamic modelling techniques currently available to inform flood
38 risk assessment and management (Prieto et al., 2021; 2022; Han, 2011; Mignot and Dewals, 2022), many
39 open questions remain as reflected for instance in the list of ‘*Twenty-three unsolved problems in hydrology*’
40 (Blöschl et al, 2019b) and in the program of the HELPING decade of the International Association of
41 Hydrological Sciences (IAHS). Two particularly timely challenges in flood risk management relate to
42 (1) improving spatial predictions of urban flooding and the quantification of their uncertainties (Skougaard
43 et al., 2017; Hooker et al. 2023), and (2) evaluating the effectiveness and efficiency of non-structural
44 measures (e.g., nature-based solutions, dam operation rules) to mitigate flood hazard (Guido et al. 2023;

45 Pelckmans et al., 2023; Fernández-Novoa et al., 2023). The papers in this special issue contribute to
46 addressing these two challenges, as outlined in the next sections.

47 **2. Challenge 1: Improving spatial predictions of urban floods and quantification of their uncertainties**

48 Societies face fast-growing urbanization and cities development, which increase the frequency, severity and
49 impacts of extreme events (Skougaard et al., 2017). Prediction of flood extent and flow depth in urban pluvial
50 flooding is a major scientific and practical challenge. Two-dimensional hydrodynamic models (Abebe et al.,
51 2019; De Almeida et al., 2016) are nowadays complemented by data driven approaches for flood hazard
52 mapping (Costabile et al., 2017; Guo et al., 2022). The latter are comparatively less demanding in
53 computational resources. Data driven models are known to perform well in domains for which they have
54 been trained, while a remaining challenge is how to transfer such models beyond their training domain (e.g.
55 Kratzert et al., 2019). In this special issue, Seleem et al. (2023) investigate the transferability of data-driven
56 models, particularly, convolutional neural network (CNN) and random forest (RF), to emulate a 2D
57 hydrodynamic model (TELEMAC-2D) in three neighbourhoods in Berlin. The data driven models were trained
58 to map topographic, land cover and precipitation variables to observed flood water depths. The depth of a
59 depression was found the most influential predictive feature, for both CNN and RF. The models' performance
60 was assessed by comparing the water depths and inundation extents predicted by the data driven models
61 against TELEMAC-2D outcomes. The authors found that CNN performed better than RF to generalise beyond
62 the training domain and to benefit from transfer learning. The study highlights the importance of collecting
63 extensive training and testing datasets, as well as the potential offered by data-driven methods for flood
64 hazard mapping in urban environments.

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

78 **3. Challenge 2: Flood mitigation using non-structural measures**

79 Nowadays, flood risk management increasingly relies on measures which do not involve the construction of
80 grey infrastructures. In this move, nature-based solutions (NBSs) have gained popularity, given their capacity
81 to enhance flood resilience while delivering side-benefits. The International Union for Conservation of Nature
82 (IUCN, 2022), the World Bank Group, and the World Resources Institute (WRI) define NBSs as “actions to
83 protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges
84 effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (IUCN,
85 2022). Therefore, NBSs are often regarded as low- or no-regret options that provide benefits for both people
86 and the environment (Faivre et al., 2017; European Commission, 2024). Examples of NBSs are reforestation
87 and afforestation, wetland restoration, and sustainable land management practices which reduce runoff.
88 Although NBS have proved effective in reducing and/or delaying flood peaks and volumes in urban or coastal
89 areas, they are still not mainstream due to limited knowledge and testing compared to more traditional
90 engineering solutions. A current key challenge is how to incorporate NBSs into hydrological and
91 hydrodynamic models.

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

104 Current knowledge on how mangroves can attenuate high water levels in large-scale deltas is restricted to
 105 modelling studies which did not capture the complex geometry of channels intertwined with intertidal
 106 wetlands or small-scale studies which only quantified attenuation inside mangroves. In this special issue,
 107 Pelckmans et al. (2023) present a delta-scale hydrodynamic model, accounting for complex landforms, for
 108 the case of the Guayas delta (Ecuador), which is the largest estuarine system on the Pacific coast in Latin
 109 America. The authors used measurements of water depth in the mangroves to calibrate the mangrove
 110 platform elevation. The delta-scale model captured the propagation of high-water levels during a spring tide,
 111 despite limited data availability. The authors make the following key contributions: (i) mangrove elevation
 112 and the presence or absence of mangroves is more important than mangrove-induced drag (and hence
 113 mangrove vegetation properties) in determining high water levels across the delta; (ii) the elevation of
 114 intertidal flats, located near the downstream end of the delta, has less effect on along-channel attenuation
 115 than upstream-located wetlands; and (iii) the degree of channelisation inside the mangrove forests
 116 determines high water levels both upstream and downstream. Therefore, mangroves with a lower surface
 117 elevation, lower vegetation density, and higher degree of channelisation favour attenuation of high-water
 118 levels in the deltaic channels. Future research could apply the methodology proposed by Pelckmans et al.
 119 (2023) in combination with freely accessible global remote sensing data to cover a wide variety of river deltas
 120 and evaluate the potential of conserving wetlands as NBSs for reducing flooding in river deltas.

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

135 4. Conclusion

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

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

143 In line with Challenge 2, Guido et al (2023) showcase a simulation-based integrated methodology for the
144 optimal design and positioning of NBSs to mitigate hurricane-induced flood hazard. In the context of
145 assessing the effectiveness of mangroves at attenuating the propagation of extreme sea levels through large
146 (order of 100 km²) estuarine or deltaic systems, with complex geometry formed by networks of branching
147 channels intertwined with mangrove and intertidal flat areas, Pelckmans et al. (2023) showed that the wide
148 range of observed and modelled attenuation rates can be partly explained by variations in the wetland
149 platform elevation and degree of channelization, in addition to vegetation properties. Using a validated
150 hydrodynamic model of a case study in Portugal, Fernández Novoa et al. (2023) present a strategy to adapt
151 the operating rules of existing infrastructure, namely multipurpose dams and reservoirs, to mitigate extreme
152 floods, achieving a reduction in flooded areas of up to 30%.

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

159 Looking ahead, the 2030 Agenda for Sustainable Development places great emphasis on flood risk reduction
160 and the interactions between floods and poverty, availability of flood, access to healthcare, water supply,
161 infrastructure, urban development, adaptation to climate change and the preservation of ecosystems. The
162 2030 Agenda highlights the urgent need to reduce flood risks. Indeed, a major disaster can wipe out the
163 economic and social progress that a country has taken years to achieve (Bello et al., 2021). In order to achieve
164 the Sustainable Development Goals by 2030, in particular Goal 6 ("safe water and sanitation for all"), and to
165 move towards successful flood risk management and planning, we need to continue research and take rapid
166 action to improve flood forecasting (e.g. flash floods) and impact-based forecasting, reduce vulnerability and
167 exposure, and adapt mitigation strategies that include NBS (e.g. by adapting urban planning to incorporate a
168 combination of NBS and other measures in a holistic way).

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