Integrated flood risk management as a tool to achieve UN Sustainable Development Goals

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Floods are the most frequent type of hazard around the globe, affecting more people than any other natural hazards. A total of 222 floods were recorded in 2021 with approximately 30 million affected people (www.emdat.be/database). In 2030, this number could rise to 54 million/year according to the World Resources Institute, despite large infrastructure investments made to mitigate disaster risk. When considering the direct (e.g., loss of life, physical damage of assets and infrastructure) and indirect (e.g., societal disruption, business interruption, environmental damage) consequences of floods, it becomes evident that high vulnerability and lack of flood resilience can undermine countries' progress towards reaching the Sustainable Development Goals (SDGs), set by the United Nations (UN). **Figure 1** shows two areas with a high vulnerability to floods, and measures to increase resilience.

Floods influence the sustainable development of countries in several ways:

- Floods impact people's health and well-being (SDG 3), which in turn worsens existing poverty, especially in developing countries (SDG 1),
- Floods may slow down or even stop the progress towards a sustainable economic growth (SDG 8), sustainable industrialisation and innovation (SDG 9), and the related development of inclusive, safe, resilient, and sustainable cities and human settlements (SDG 11),
- Floods impact key sectors for eradicating hunger, such as agriculture (SDG 2). Still, floods are a vital source of freshwater (SDG 6) in semi-arid or arid regions, hence there a coexistence of flood and drought needs to be considered,
- Floods may cause several forms of water pollution, e.g., when damaging sanitation facilities, impeding safe and affordable access to drinking water (SDG 6), and may at the same time impact water ecosystems and services they provide (SDG 14),
- Floods may increase their magnitude and frequency due to changing hydro-climatic conditions in the future; which accelerates the need for incorporating climate policies (SDG 13).

Nonetheless, strong linkages exist between the different SDGs, hence, floods may also have an indirect influence on the sustainable development of a certain area. For instance, poverty, migration to cities or uncontrollably growing urbanisation exacerbate flood impacts by an increase in vulnerability (**Figure 1 left**). Accordingly, increasing flood resilience is an important part of reaching the goals set by the UN. Reducing vulnerability by, at the same time, increasing the resilience, requires the adoption of Integrated Flood Risk Management (IFRM), whose key components (**Figure 2**) are:

- Working in different temporal frames (i.e., during prevention, preparedness, response, and recovery phases of a disaster),
- Working at different spatial scales (from the very local to the global/catchment level) and also beyond national borders (e.g., transboundary catchments) for implementing climate-related policies,
- Addressing the different components of flood risk (to reduce the hazard, exposure, or vulnerability),
- Adopting the best mix of structural and non-structural mitigation strategies, in a multi-objective perspective, considering ecological goals and compound events, which means the mitigation of co-existing natural (earthquakes, landslides, hurricanes/typhoons, etc.) or human made (nuclear, biological, etc.) hazards,
- Ensuring public participation at all levels of decision-making, as risk management needs to be open, transparent, and communicative among all stakeholders.

Figure 1 | (Left) Residential area in Bangkok, Thailand, with high vulnerability, and (right) increased resilience of houses by technical flood protection measures implemented in the United Arab Emirates.

Implementing IFRM requires a holistic view on drivers, system state descriptors as well as responses (**Figure 3**). Drivers, such as climate and socio-economic changes are processes that act autonomously on changing the state of the system. However, responses are purposeful measures, which can be implemented in a holistic manner.

Given the complex interplay among natural/physical phenomena and the anthropogenic alterations of the system, such a holistic understanding requires the adoption of comprehensive, integrated and sophisticated modelling tools, addressing the various steps of IFRM. These are data acquisition, hydrologic/hydraulic modelling, damage potential analysis, ecological impact assessment, design and sizing of flood protection measures (including alternatives and optimization), and stakeholder involvement among several others (**Figure 2**). Nonetheless, an "adaptive/flexible" implementation of IFRM is required to properly consider existing uncertainties associated with complex models, (possible) data limitation, and changing boundary conditions due to climate change and urbanisation.

These challenges are nicely exemplified through studies and projects in which members of the IAHR Technical Committee on Flood Risk Management have been involved. We shed light here on a small sample of them, with the aim of emphasising the instrumental contribution of the IAHR community for improving IFRM across the globe, and hence our contribution to achieving the UN SDGs. A focus is thereby set on SDG 11 (Sustainable cities and communities) and SDG 13 (Climate action), which appear as the backbone of most IFRM-related projects.

The challenge of modelling compound flood processes in a coastal environment as well as the complex physics-human interplay is addressed in the ongoing STARS project, funded by the Ministry of Education (Ministry of Human Resources Development), Government of India. The study area is the low-lying Brahmani-Baitarani river basin (**Figure 4 left**), located in the eastern part of India, which faces backwaters from sea surges, fast sea-level rise (+ 3.8mm/year), climate-induced extreme preci-pitation combined with increased runoff from urban/peri-urban areas, sub-optimal reservoir operation, riverbed changes due to upstream mining and agriculture, as well as floodplain en-croachment. As many tangible and non-tangible benefits for human well-being can be reaped from coastal areas, their pro-tection from natural hazards and environmental degradation is key to the achievement of sustainable development. A novel short-to medium-range flood-forecasting system is under development in the basin, integrating more processes than before

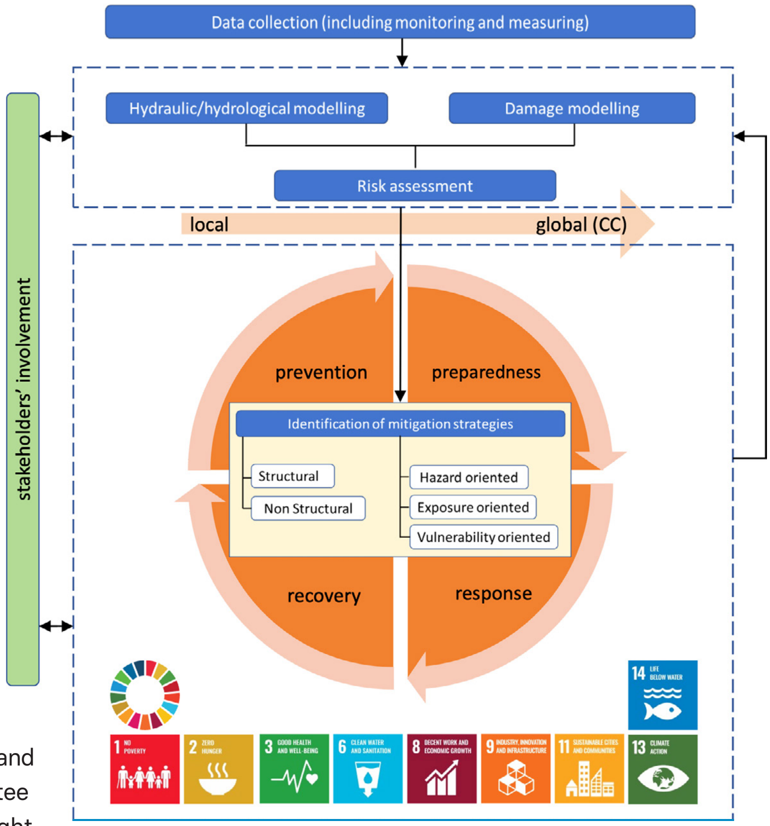
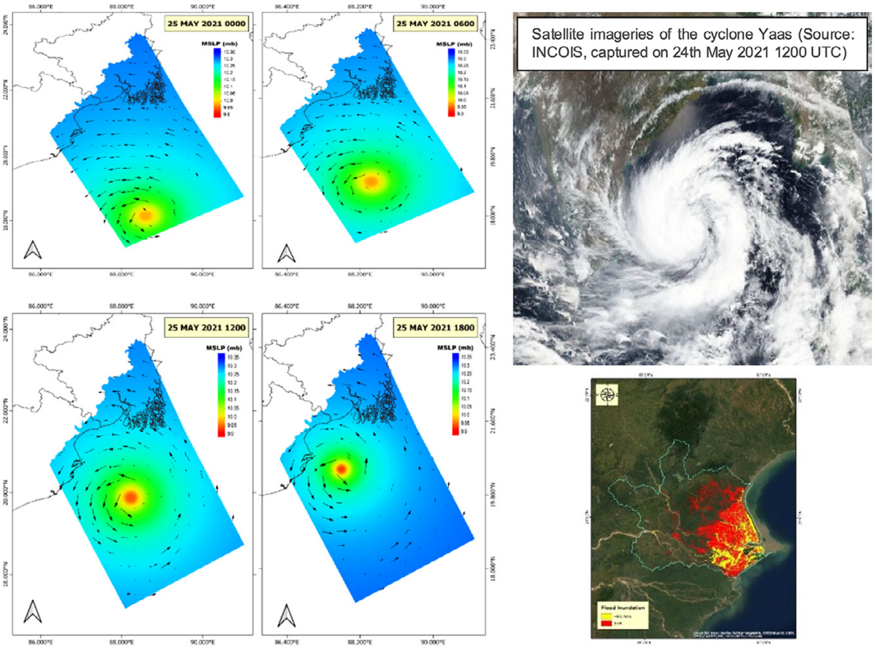


Figure 2 | Components of Integrated Flood Risk Management (IFRM) and associated SDGs.

(i.e., rainfall-runoff, hydraulic routing, sediment flux, land use and river morphology changes due to anthropogenic activities, reservoir operation rules, real-time sea level), thus increasing the capability of local communities to deal with flood events.

Integrated flood modelling is also key for enabling a robust appraisal of combined pluvial and river floods. These two processes interact closely in relatively small catchments, characterised by a quick hydrological response, as well as in urban areas. The complexity of urban environments, characterised by multiple pathways and flow-sensitivity to micro-scale topographic features, still requires deeper research, based on laboratory experiments, to improve our understanding of processes and accuracy of numerical modelling tools. An ongoing initiative in this direction is the EU-funded Co-UDlabs network of experimental infrastructures (https://co-udlabs.eu/) that enables tackling complex, multidisciplinary open questions related to urban drainage systems (like the transport and turbulent dispersion of contaminants in urban flooding or other polluting agents such as macro- and micro-plastic) by means of cooperative research between 17 facilities across Europe and the wider scientific community.

Figure 3 | Interplay between intrinsic and extrinsic variables in IFRM.



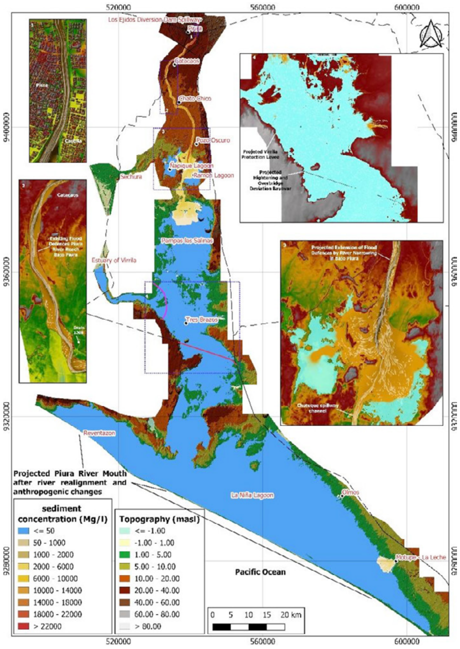


Figure 4 left | Spatial distribution of simulated wind vectors and pressure fields over the study region during cyclone 'Yaas' and flood inundated area in Brahmani-Baitrani Delta region.

Figure 4 right | 2D hydraulic and fine sediment transport modelling along Piura river until the mouth of the river.

Inter- and transdisciplinary approaches are also necessary when assessing the impact of hydro-climatic change on reservoirs. Reservoirs provide a unique opportunity for controlling floods and delivering a wide range of services. Within the ongoing project DIRT-X, as part of AXIS, an ERA-NET initiated by JPI Climate, a consortium of partners from five European countries investigates how changing climate- and socioeconomic conditions alter future water availability and soil erosion processes in the catchment. Based on these findings changes in the storage volume of reservoirs due to sedimentation and the influence on services they provide to different economic sectors will be determined. This newly gained knowledge serves as the basis for the implementation of future reservoir management to ensure sufficient retention volume for more frequent and more severe flood events occurring in the future (https://dirtx-reservoirs4future.eu/). Since reservoirs are often used as multipurpose structures, this initiative also serves SDG 6 (Clean water and sanitation) and SDG 7 (Affordable and clean energy).

A meaningful example of stakeholder engagement is represented by flood risk management activities carried out in the Piura River basin in Peru. One-hundred and fifty years of anthropogenic interventions, such as channelization and river diversion towards an artificial river mouth, have resulted in complex issues regarding the river morphology in this system (https://www.youtube.com/watch?v=HiS-azK8WgY).

After a destructive El Niño flood event in 2017, large-scale actions have been performed for addressing the existing flood risk. Besides advanced hydro-morphological modelling, which is strongly required for a comprehensive understanding of the river morphodynamic (**Figure 4 right**), more than 100 workshops and meetings with social, environmental, and political stakeholders had taken place, with the aim of promoting sustainable engineering measures.

Engagement of stakeholders is not only a key element in the decision-making phase; their involvement from the design phase is vital to turn resistance to the implementation of risk reduction measures into endorsement and support. A remarkable example of a collaboration of scientists and practitioners is the award-winning MOVIDA initiative in the Po River District, Italy (https://sites.google.com/view/movida-project). Tailored models and related IT tools were developed in accordance with the European Union (EU) Floods Directive (2007/60/EC) requirements for the appraisal of flood damage in the district. The models were then applied in a participatory process to inform on the prioritisation of flood risk mitigation strategies (www.gwptoolbox.org/case-study/italy-movida-models-and-tools-integrated-damage-assessment).

Further acknowledging the central role of the human component is a necessary milestone to leap forward towards effective, sustainable, and fair flood risk reduction strategies (**Compare figure 5**). This is a prerequisite to achieve SDGs 1 (No poverty) and 10 (Reduced inequalities). Worldwide, the population at risk of flooding is mostly a part of underprivileged socio-economic groups. Following similar assessments in the United Kingdom (for coastal flooding) and in the United States of America (including pluvial flooding), a recent study conducted in Belgium highlighted that underprivileged population is significantly more exposed to river flood hazard for moderate floods, and this trend is further exacerbated in the case of extreme events (www.frontiersin.org/articles/10.3389/frwa.2021.633046/full). Similarly, energy-efficiency, land conservation and improved mobility require spatial planning policies, such as urban densification, which may contradict the needs of flood risk reduction (https://doi.org/-10.1016/j. jenvman. 2018.07.090). Disentangling such a dilemma is only possible through the lens of a comprehensive system-approach, in which the main societal needs and their couplings are evaluated in an integrated way.

Ultimately, the IFRM framework is an essential part of a broader coordinated effort to make societies more resilient, carbon-neutral, and sustainable. The implementation of this framework is therefore indispensable for the achievement of several targets of the SDGs. However, large differences exist in its implementation, so that different priorities and related actions can be identified to ensure the adoption of IFRM in the near future. In low-income countries, the improvement of knowledge of both the natural phenomena and the vulnerability pattern of affected areas is the future challenge to increase the resilience of cities and human settlements and, hence, people's health and well-being. An increased adoption of concepts like best-mix strategies (including risk awareness campaigns and community empowerment), multi-risks solutions (including nature-based ones) and participatory decision-making (based on a wider implementation of Multi Criteria Analysis) is already conducted in many high-income countries. However, IFRM is a dynamic framework and continuous development is necessary to cope with challenges related to hydro-environment engineering and research to achieve the SDGs.

Figure 5 | Recent adapted construction in floodplains in Belgium as a part of IFRM.

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