Flood events have devastating impacts on communities around the world, resulting in loss of life, property damage and severe disruption to national economies and global trade. The frequency of such flood events has increased significantly over the past few decades, to the point where flooding is now the most common type of natural hazard (Figure 1). The increasing severity of disastrous floods, particularly in regions where flow regimes are heavily engineered and regulated by many dams, reservoir and other infrastructure, challenge current science-policy paradigms with respect to flood risk and undermine public trust in flood risk management. We argue for new scientific paradigms and tools that capture the profound uncertainty and complexity surrounding climate, environment and societal futures. Also needed is more robust public participation in flood management processes to raise awareness of trade-offs endemic to Anthropocene flood management.

We use riverine flood disasters in 2019 as examples to reveal a global narrative about more extreme events, societies being ill-prepared for them and the increasing role of human activity in influencing environmental change. This global flood year began with the convergence of a very active monsoon and a slow-moving tropical low-pressure system creating unprecedented rainfall for Australia’s north Queensland coast in January and February. The City of Townsville, downstream of the Ross River dam, experienced severe flooding. The event resulted in three direct and two indirect fatalities and more than $727 million in insured property losses. In March and April, three massive rainfall events created flash flooding across 25 of Iran’s 31 provinces, where major rivers are managed by dams and reservoirs. This event caused 76 fatalities and more than $2 billion in damage. The combination of heavy rain and melting snowpack in the Ottawa River basin, which is regulated by a series of reservoirs, produced record-breaking flood peaks in the Canadian cities of Ottawa and Gatineau and surrounding communities in April. Record-breaking spring floods also occurred across the Mississippi River and its tributaries, a heavily managed water system in the United States, causing four casualties and more than $12.5 billion in damage.

Public discourse about these events centred on the efficacy of infrastructure design and management and the operational rules that govern day-to-day decision-making. Australians questioned whether the management of Ross River Dam contributed to flooding in Townsville when a large amount of water was released downstream (Smee, 2019). Iranians in many of the affected areas wondered why large existing reservoirs did not protect them from flooding (ISNA, 2019). Reservoir operations also came under scrutiny in the Ottawa floods (CBC, 2019), in response to public concerns, and in the United States, where residents blamed the US Army Corps of Engineers for the mismanagement of hundreds of reservoirs in the Mississippi River Basin.
In the latter case, local residents were critical of opening Keystone Dam and releasing a large amount of water into the Arkansas River, which had a particularly severe impact on the city of Sand Springs, Oklahoma.

These real-time operational concerns arose from deeper, more fundamental issues associated with infrastructure planning and design, human settlement in the floodplain and perceptions of risk. Also, they raised serious concerns about the credibility of official floodplain risk maps. For example, in the Townsville and Ottawa flood events, many affected properties were uninsured because they were considered to be in flood-free zones, but now face the prospect of becoming uninsurable. In Iran, many of the flooded roads and properties were built in the last few decades in areas now part of the floodplain.

As we explain below, the above issues arise because traditional scientific solutions to flood risk management are unable to adapt to the Anthropocene. We highlight two grand challenges facing science and society and outline the tools required to meet these challenges. The overarching goal is to inform decision-making related to land use, floodplain management, infrastructure design and operational protocols. The ability to capture the uncertainty and complexity of future flood risk and society’s exposure and vulnerability to such hazards is especially relevant.

1 | EMBRACING UNCERTAINTY

Both scientific and engineering practice emphasizes deterministic solutions despite the fact that the magnitude and frequency of flood hazards are changing in a deeply uncertain manner due to compound effects from a range of natural and human drivers. Anthropogenic climate change may potentially alter the intensity, duration, frequency and spatial distribution of precipitation, as well as the resulting streamflow, coastal inundation, storm surge, tropical cyclones and hurricanes. Dams and reservoirs, while perceived to modify streamflow regimes in "known" engineered ways, often add significant uncertainty to flood risk. Their operating rules are typically confidential and can be ad hoc at the time of crisis to address emergencies such as dam security. Runoff generation and river routing mechanisms are changing in a variety of ways due to urbanization, land cover/land-use change, artificial drainage and river training, as well as climate warming effects such as changed regimes of snowmelt and rain-on-snow floods. The combined effects of changing human and physical drivers produce profound uncertainty because of our limited understanding of how they interact and evolve under conditions that differ from those experienced in the past.

Milly et al. (2008) argued that changing climate and land-use patterns of the past are no longer an adequate basis upon which to predict the future, and that "stationarity is dead." They called for development of non-stationary probabilistic models of environmental variables to optimize water systems. The need for new models and tools is nowhere more apparent than for the stationarity-based notion of return period, which remains the basis for floodplain analyses and resulting flood insurance measures; a notion that can be misleading and augment vulnerabilities. Statements like what today is the 1-in-25-year flood could become the 1-in-5-year flood in 10 years have become common in policy discourse. Recent research efforts to enable the traditional, stationarity-based risk assessment paradigm to account for such "predicted" future trends are of limited use, however, because they are unable to capture deep uncertainties and complexities involved. In practice, they are often a modern version of the traditional, deterministic "safety factors" used to compensate for a
lack of information (Stakhiv, 2011). The classic flood risk analysis paradigm, based on best-guess estimates of how the future might look, is obsolete in the face of radically uncertain climate, environment and society.

2 | DISCOVERING COMPLEXITY AND TRADE-OFFS

The design and operation of water systems and other public infrastructure often involve multi-dimensional trade-offs between upstream and downstream users, flood and drought protection, economic growth and endangered species protection, and rural and urban needs. Engineering-based cost-benefit analysis methods focus on a small subset of these dimensions and often ignore the rest. Natural, engineered and social systems are interwoven in complex, time-varying ways and are interdependent through feedback mechanisms that are often hard to quantify and predict. Such interdependencies can result in cascading or undesired spinoff effects that are ignored in traditional engineering approaches (AghaKouchak et al., 2018; Di Baldassarre et al., 2018). In addition to direct material costs, social damage costs, including public unrest, loss of lives and long-term adverse effects on mental health that lead to post-traumatic stress disorder, depression and anxiety (Alderman, Turner, & Tong, 2012), are typically excluded from economic impact assessments, because these are hard to quantify in monetary terms (Brouwer & Schaafsma, 2013). Quantifying and navigating such trade-offs and converging on a compromise under uncertainty in the associated risks is critical.

Assessing trade-offs is further complicated by the time-varying nature and perceptions of risks at individual, community and institutional levels. These changes are linked to socio-economic interests, the development and evolution of which may be unpredictable and affected by memories of prior flood and drought disasters, and professional and social media content. A risk management paradox often emerges if no flood disaster occurs for an extended period of time in a region, due to either careful risk management or simply natural variability. For example, a prolonged drought in Iran masked flood risks for years and led to urban development in flood-prone areas. Infrastructure development discounted flood risk in favour of drought prevention. As a result, this year’s flood damage was particularly severe. The hazard community refers to this phenomenon as a loss of social memory when people have little recent exposure to flooding and thus fail to take adequate flood mitigation measures (Adger, Hughes, Folke, Carpenter, & Rockström, 2005).

Reservoirs and other water infrastructure can introduce a flood exposure paradox by creating a false sense of security for surrounding communities. While they may initially reduce the exposure to flood hazards, in the long-run they intensify development and population growth, and increase flood risks. The Ross River Dam in Australia, constructed in 1974 for Townsville’s flood protection, led to significant population growth in the downstream floodplain where residents depended on the dam for water supply. Consequently, the flood impact was felt most severely in areas that were developed over the past two decades and considered to be free of flood risk. In the Mississippi River Basin, many reservoir managers understated flood control in favour of other priorities such as commercial and recreational interests and wildlife protection. Nature-based solutions, such as creating space for water through floodplain restoration (Brouwer & van Ek, 2004), have gained momentum as a cost-effective, public awareness-raising alternative. The current generation of modelling tools is unable to represent such complex, multi-dimensional and time-varying human–nature relationships and reveal real decision trade-offs for communities and policy makers.

3 | NEXT STEPS

Recent flood events suggest that science and society are ill-prepared for the difficult decisions that lie ahead as the flood events and impacts of the Anthropocene unfold. These decisions require a new science-policy paradigm that grasps and systematically accounts for the uncertainty and complexity associated with future flood risk, based on the following three fundamental underpinnings.

3.1 | Transdisciplinary modelling and assessment frameworks

Flood research needs to broaden its focus from traditional hydrological and engineering approaches to transcend disciplinary boundaries and develop integrated models that couple relevant natural and human-driven processes, allowing the representation of dynamic interactions and feedback mechanisms that can occur at different spatial and temporal scales. To this end, climate scientists, hydrologists, water resource engineers, urban planners, economists, social and policy scientists, health scientists and policy makers need to work together to ensure the resulting models adequately represent plausible future trajectories of the human–natural water system. Such efforts can learn from recent advances in minimal, exploratory modelling that provides insight into how different natural, built and social systems might interact and co-evolve based on adaptive behavioural responses that reflect social and technological learning (Di Baldassarre et al., 2015; Safarzyńska, Brouwer, & Hofkes, 2013). Integrated modelling and assessment frameworks should allow for different levels of abstraction, facilitating learning and enabling different stakeholders to be involved in decision-making processes.

3.2 | From predictions to scenarios

The concepts of flood probability and exposure need to be re-defined to accommodate alternative future scenarios, to address the limited predictive power arising from the deep uncertainties and profound complexity of coupled human–natural systems in the Anthropocene.
Scenarios are consistent stories about the future of systems that are too complex to predict (Wiek, Keeler, Schweizer, & Lang, 2013). They cover a range of plausible futures, including rare catastrophic conditions, and their development provides a process for stakeholders to share competing views of the future (Lempert, Popper, & Bankes, 2003). Scenario generation facilitates robust decision-making, the search for solutions that work across a range of future conditions (e.g., climate change, infrastructure development, operational decisions, land-use change and policy decisions). Sensitivity analysis tools can be used to guide scenario generation by identifying dominant controls of human–natural systems (Razavi & Gupta, 2015). Recent advances in the field of Decision Making Under Uncertainty (Lempert et al., 2019; Maier et al., 2016) can help us to move away from crisp solutions that induce a false sense of security, to focus on critical scenarios that need attention, characterize associated trade-offs and enable decision-makers to think beyond “return periods” and the likelihood of floods (Gober, 2018).

3.3 | Building a science–public interface

Broad participation of community stakeholders in modelling efforts, scenario development and cross-sectoral trade-off analysis is urgently needed to ensure that scientific tools represent the interests, beliefs and disagreements of local communities, economic sectors and public institutions, and to increase the likelihood that the best-available science will be used for flood management decision-making. Social scientists have called attention to the importance of close and iterative collaboration between stakeholders and scientists and more effective communication of science for decision-making (Dilling & Lemos, 2011). In this new social framework, society becomes an active force in developing and managing uncertain and complex systems exposed to flooding rather than a passive victim of flood damage. Efforts under the European Floods Directive provide working examples for this important endeavour (Evers, Jonoski, Almoradie, & Lange, 2016). Flood modelling can facilitate knowledge co-creation by building publicly accessible physical or online facilities for scenario simulation, decision analysis and visualization.

4 | THE BOTTOM LINE

Flood systems of the Anthropocene are profoundly complex and deeply uncertain. They require a change in research and practice to embrace uncertainty, recognize and adequately represent complexities of natural–human systems, and incorporate the various stakeholders at different flood governance levels into these decision-informing and decision-making processes as a form of “soft” engineering. The proposed paradigm based on transdisciplinary science, scenario development and public engagement challenges communities to ask what kind of future they want and scientists to provide them with explorative tools that enable better management of flood risk in the Anthropocene.

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