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The Future of Floods: Smarter Risk Tools for Sustainable Water Management in a Changing Climate

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EARTH & ENVIRONMENTAL SCIENCES

Sustainable decision-making requires balancing the costs borne by today's society with those that will fall on future generations. Climate change is intensifying extreme weather, making floods more severe because a warmer atmosphere can hold and deliver a larger volume of water as precipitation. It may also be the case that severe floods are becoming more frequent as drought becomes more frequent, average conditions rarely occur, and weather oscillates between short duration wet and long duration dry extremes. Worryingly, traditional infrastructure (often designed using outdated, backward-looking models) risks failing under these evolving conditions.

Nick Martin from Vodanube LLC, and his colleagues have applied Probabilistic Risk Assessment (PRA) to flood inundation. Their research optimises current adaptation and future mitigation strategies, even while acknowledging PRA's limitations. The team demonstrates how this approach can guide more resilient water resource management, and highlights opportunities for further study.

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Sustainability and Adaptation in a Changing World

Sustainability can be defined as meeting the needs of the present, while safeguarding the ability of future generations to meet theirs. Central to this concept is the responsible use and shared stewardship of resources. Management of water and natural resources, land-use planning, and safety regulations must adapt in response to significant shifts in external drivers, such as climate, to ensure sustainability.

Human-induced factors are driving climate shifts that exceed the range of past observations. Global temperatures are projected to rise by more than 1.5 °C between 2030 and 2052, compared to pre-industrial levels. In 2024, the world experienced an unprecedented year of extreme weather, with 41 additional days of dangerous heat, alongside record-breaking precipitation and severe droughts —events like these highlight the limits of relying solely on historical patterns for planning. To manage this uncertainty effectively, we must apply scientific methods to test our understanding, refine what we know, and reduce knowledge gaps, so that we can ensure better sustainability in a rapidly changing world.

Probabilistic Risk Assessment: Planning for the Unknown

Sustainability and adaptation are fundamentally about planning for the future, but the future is inherently unobservable and largely unknown. Traditional engineering approaches, which rely heavily on past experience and historical observations, assume that next year's conditions will fall within the range of the past 30, 50, or 100 years. Nevertheless, today's climate is neither static nor stationary. Highly variable phenomena, like weather, provide only a tiny snapshot of what could occur, and rare or extreme events cannot be reliably predicted from historical records alone. As climate change accelerates, this backward-looking approach offers limited guidance for planning and resource management, making proactive adaptation by current generations essential to ensure sustainability.

Effective water resource management relies on planning for uncertainty, using designs and technologies that account for knowledge gaps, and aims to prepare for future conditions beyond historical experience. One powerful approach for navigating this uncertainty is Probabilistic Risk Assessment (PRA). PRA is a logical, step-by-step method for analysing risks in complex systems. By exploring multiple scenarios, PRA can model vastly different future conditions, helping decision-makers plan for a range of possibilities. PRA is also complemented by weather attribution studies, which are scientific analyses that estimate how human-driven climate change has altered the likelihood or intensity of specific weather events. By providing probabilities for the magnitude of future events, these models help planners account for both scientific and planning uncertainty.

While PRA is a mature technology, long used in aerospace, nuclear, and radioactive waste sectors, its applications are now expanding. Recent studies have applied PRA to evaluate environmental risks from toxic materials, deep well injection of hazardous substances, seismic hazards, and addition of fluoride to treat water supplies.

Probabilistic Risk Assessment: Turning Risk into Resilience

The researchers initially used PRA to guide sustainable water management and adaptation, tackling challenges where infrastructure was designed for historical conditions—their study explored the benefits of PRA for sustainability planning, as well as its limitations. The scenario combined real climate and weather data from the Frio River basin near Uvalde, Texas, with a synthetic topography and land-use design.

By creating a synthetic site, the study developed an efficient framework for exploring adaptation and mitigation strategies in water management. Combined with actual climate and weather data, it demonstrated how PRA can help balance costs between the present and the future, highlighting its utility for sustainable resource planning.

Analyses conducted by other, independent researchers identify two major shifts in extreme events for the 2020s compared with the 2000s: **severe three-month droughts are now five times more likely, and extreme precipitation events have increased at least fourfold**. These changes make traditional, historically based engineering designs and planning insufficient, potentially locking future generations into continuous mitigation expenditures.

The study applied a simple PRA, focusing on one key scenario in which flooding could occur under a changing climate. While the team acknowledged its limitations, their approach provided a flexible template that could be adapted to other sites, and highlighted the dangers of land-use planning based on outdated, backward-looking engineering assumptions.

From Risk to Resilience: Circularity in Holistic Planning

Circularity is closely related to yet distinct from sustainability. It emphasises a closed-loop resource life-cycle, where materials are re-used and nothing ends up as waste. Practices like regenerative agriculture (treating farms as connected, self-renewing systems) and sponge city planning (using natural areas like parks, wetlands, and streams to manage stormwater naturally), bring this idea to life, offering holistic ways to manage natural resources.

In practical terms, these approaches encourage planners toward strategies that deliver lasting benefits, moving beyond the traditional "build now, pay for damage mitigation later" mindset, where infrastructure is eventually removed or rebuilt. While PRA is excellent at assessing risk, failure, and costs, it does not capture the positive impact of holistic, regenerative strategies. By extending PRA into a probabilistic cost–benefit framework, planners can weigh both risks and rewards, supporting circular, sustainable decisions that enhance resilience over the long-term.

Looking Ahead: Expanding PRA for Sustainability

Nick Martin and his team applied PRA to flood risk in a changing climate, showing how the method can inform sustainable water management. As extreme weather grows more frequent and unpredictable, their analysis highlights how PRA can help balance the costs of today's adaptation with tomorrow's mitigation, especially for infrastructure built to outdated climatic standards. By drawing on weather attribution studies, their approach also brings planning and scientific uncertainty into practical consideration.

The next chapter for the team is ambitious: a full-scale demonstration at an actual site, using comprehensive, site-specific data. This new phase will put theory into practice, testing how PRA can guide real world decision making. Their vision points to a future where stewardship means more than just defending against floods with outdated rules and designs. Instead, it calls for holistic strategies, protecting floodplains as vital spaces for water storage, habitat, and other non-development benefits, while phasing out construction in areas wherever possible.

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MEET THE RESEARCHER

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Nick Martin obtained a Bachelor of Science in Geophysics from Virginia Tech, and a Masters of Science in Hydrogeology, from Standford University, along with a Bachelor of Arts in International Studies, and a Master of Arts in International Relations, both from Johns Hopkins University.

Mr Martin is a surface water and groundwater hydrologist and software developer, with more than 20 years of experience. His work has focused on risk assessment, risk mitigation, reliability, resiliency, and sustainability analyses, related to climate change and legacy infrastructure, on natural and engineered systems. He has specialised in probabilistic analysis and modelling, to quantify uncertainty and define environmental and economic risk. His technical interests include: uncertainty analysis for decision support and data assimilation as part of water movement, transport modeling, machine learning, and deep learning studies. He has also designed and implemented numerical methods, extension modules, and standalone computer programs.

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FURTHER READING

Martin N, Peña F, Powers D (2025) Probabilistic Risk Assessment (PRA) for Sustainable Water Resource Management: A Future Flood Inundation Example. *Water* 17(6): 816. https://doi.org/10.3390/w17060816