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A structured framework for context-based selection of DMDU approaches in environmental water management

Farkhondeh Sadat Hashemi Madani [a], **Avril Horne** [a], **Andrew John** [a]

[a] *Managing climate change and variability Lab, Department of Infrastructure Engineering, University of Melbourne, Australia*

Email: hashemimadf@unimelb.edu.au

Abstract: Freshwater ecosystems have experienced significant declines due to various uncertain factors that threaten their sustainability including pollution, land use change, water extraction, and climate change. Climate-driven changes affect the hydrological cycle and ecohydrological processes, with implications for both human use of water resources and aquatic ecosystems. Climate change also poses significant challenges for decision makers by breaking the assumption of stationary risk through long-term shifts in climate extremes, and by introducing deep uncertainty where the scale and direction of future risks cannot be reliably predicted. Simultaneously, land-use change, driven by urbanization, agricultural expansion, deforestation, and industrial activities, affects water quality as well as hydrological processes such as surface runoff, groundwater recharge, and sediment transport, exacerbate pressures on freshwater ecosystems. To overcome these challenges, decision makers must identify and implement robust adaptive responses that acknowledge future uncertainties and ensure sustainable planning. This requires a shift where decision-making moves beyond the traditional 'predict-then-act' paradigm to Decision Making under Deep Uncertainty (DMDU) approaches which are based on 'monitor and adapt' paradigm. DMDU approaches offer a way to acknowledge and adapt to uncertainty by incorporating robust and flexible strategies that ensure acceptable system performance across a wide range of future conditions and evolve alongside changing conditions. The broad variety of these approaches makes it challenging to select and apply the most appropriate one for a specific decision context. While some studies examine the components of the different DMDU approaches and offer taxonomies to facilitate comparison among them, there is still little guidance on selecting the most appropriate approach based on the context and decisions attributes.

This research presents a structured framework to guide the selection of the most appropriate DMDU method for different environmental water decisions, helping decision-makers think more systematically by considering the nature of the decisions. To this end, using a snowball literature review and practitioner input, five broad categories of environmental water management decisions are identified including: (i) increasing the share of environmental water through caps, reserves, or entitlements; (ii) applying licence conditions and restrictions (e.g., changes to a water allocation plan); (iii) optimising storage operation rules; (iv) enhancing conservation and resilience (e.g., riparian and wetland recovery or reconnecting rivers with floodplains by providing managed high flows); and (v) implementing infrastructure and engineering solutions (e.g., regulators, wetland pumps, or stormwater structures). The inherent characteristics of these decisions, including their strategic level, potential for lock-in, level of stakeholder engagement, and inherent risks such as disastrous consequences, maladaptation, and conflict generation, are then considered to characterise the decision context and help align the decisions with different DMDU approaches. Different DMDU approaches, including Robust Decision Making (RDM), Many-Objective Robust Decision Making (MORDM), Dynamic Adaptive Planning (DAP), Dynamic Adaptive Policy Pathways (DAPP), Info-Gap Decision Theory (IGDT), Eco-Engineering Decision Scaling (EEDS), Robust Optimisation (RO), and Engineering Options Analysis (EOA), are then characterised using six features: policy architecture (protective vs dynamic adaptivity or static robustness), robustness metrics (e.g., satisficing, regret), vulnerability analysis tools (e.g., scenario discovery, adaptation tipping points), capability for managing trade-offs, depth of stakeholder engagement, and emphasis on monitoring.

By aligning the DMDU approaches' characteristics with decision attributes, a structured framework is shaped. In this framework, policy architecture aligns with a decision's strategic level and potential for lock-in; the way approaches conduct vulnerability analysis determines their suitability for different levels of maladaptation risk; decisions with a high potential for disastrous consequences are best addressed through regret-based robustness metrics; and the potential for conflict is linked to the approach's ability to manage trade-offs and the extent of stakeholder engagement it supports. These alignments provide a transparent mapping from decision context to DMDU approaches, ultimately arming environmental water managers with the right tools to address deep uncertainty in the decision-making process.

Keywords: *Decision Making, Deep Uncertainty, Robustness, Environmental water Management, Environmental Flows*

