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Socio-ecological systems modeling on water resources management under uncertainty: A literature review.

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Scientists and decision-makers globally confront systemic challenges posed by the intertwining issues of water scarcity and climate change. These challenges give rise to cascading impacts across ecological and socioeconomic systems, often exacerbated by feedback loops and unforeseeable consequences (UNDRR, 2021). As non-linear changes loom, the reliance on consolidative modeling becomes dangerous, risking the activation of disastrous tipping points with severe implications for both nature and humans (Kreibich et al., 2022). The costs associated with neglecting uncertainties in modeling and policy spans diverse domains, including ecosystems, income, employment, capital value, insurance, etc. (UNDRR, 2022; Parrado et al., 2019; Adamson and Loch, 2021). This aligns with the concept of Knightian or deep uncertainty, where the external context, system dynamics, and conflicting outcomes are not fully known or agreed upon (Knight, 1921; Marchau et al., 2019; Lempert et al., 2006). A growing scientific and policy consensus emphasizes the need to move beyond traditional notions of optimality and deterministic prediction in conditions of deep uncertainty. Resilience and robustness emerge as crucial concepts, requiring the development of socio-ecological system (SES) models that explicitly quantify uncertainties (Adamson and Loch, 2021; Di Baldassarre et al., 2016; IPCC, 2021; UNDRR, 2021).

Recent research in SES, including coupled human and natural systems and socio-hydrology science, offers innovative modeling techniques integrating human and natural components. These techniques account for feedbacks and heterogeneity between systems, improving insight and the ability to predict tipping points (Gain et al., 2021). Recent studies demonstrate the potential of linking coupled models of human-water systems with sensitivity analysis and multi-system ensembles for robust water management policies (Basheer et al., 2023; Smith et al., 2021).

This review initially identified 2160 papers, filtering them to 198 studies that account quantitatively modelling in, both human and water systems. The geographical focus spans the USA, Europe, Australia, the Middle East, South America, China, and East Africa. The models range from piecewise equations to full-fledged representations. However, structural uncertainties are seldom

explored, with only 3.5% of studies conducting multi-model ensemble experiments. This highlights a significant oversight in recognizing biases from simplifications. Conversely, parameter uncertainties are more frequently addressed (20.2%), focusing on hydrology, groundwater, behavioral, infrastructure, climatic, economic, and agronomic variables. Input uncertainties, notably contemporary (discharge data) and future (climate change) inputs, are extensively studied (148 out of 198), employing methods like expert judgment and Monte Carlo simulations. Despite this, the review highlights a limited exploration of structural uncertainties and the potential inadequacy of linear piecewise equations, emphasizing the need for more nuanced and robust approaches to enhance the accuracy and reliability of socio-environmental systems modeling.

Based on this study, we make the following recommendations to mainstream uncertainty quantification into SES modeling: (i) Quantify parameter and structural uncertainties within systems, (ii) Quantify structural uncertainties between models, (iii) Input uncertainties must be more thoroughly assessed and model assumptions systematically revised, (iv) Deliver actionable science that mainstreams uncertainty quantification into decision making, (v) Establish balanced stakeholder engagement and clear and transparent science-policy engagement rules, (vi) Balance complexity and usefulness to keep the model relevant.