Eco-engineering decision scaling (EEDS): A new approach to integrating ecosystems within engineered water management systems

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Abstract

Eco-Engineering Decision Scaling (EEDS) is an approach that explicitly and quantitatively explores tradeoffs in stakeholder-defined engineering and ecological performance metrics across a range of possible management actions under unknown future hydrological and climate states. The EEDS framework significantly contrasts with approaches typically used to assess the environmental impacts of water infrastructure projects by evaluating tradeoffs in the initial stages of planning and development rather than as a post-hoc "impact" assessment. Such early evaluation of ecosystem vulnerability is needed to reveal a range of potential design and management options in complex social-ecological systems.

EEDS has been designed as a stakeholder-centered process mediated with technical inputs, which assumes that engagement with and service to stakeholders is critical to the ultimate success of adaptive resource management in a multi-institutional management context. It follows an iterative five-step process that includes defining system performance criteria, building a systems model, conducting a vulnerability analysis, evaluating options, and identifying a preferred decision (and, if necessary, reevaluating management options and/or criteria).

The EEDS approach was developed by a joint team of ecologists and with the support of the US National Science Foundation to integrate adaptive species and ecosystem management, especially when water infrastructure design and operations decisions may be an important component of the management decisions. It is based on a more general method of decision scaling that was developed within the water resources management community to address complex multi-stakeholder decisions associated with high levels of uncertainty in future hydrological conditions. Although newer, EEDS is rapidly growing in acceptance: a national-scale application of EEDS is underway in Mexico with the Mexican Water Commission (CONAGUA) and WWF-Mexico, while a guidance publication published by the US federal government UNESCO water center ICIWaRM (housed by

the US Army Corps of Engineers is forthcoming in late 2017 / early 2018.

Keywords: *ecosystems; infrastructure; uncertainty; vulnerability assessment*

1. Introduction

The desire to manage water sustainably has broad support, but defining "sustainable" water management has proven difficult for policymakers with instruments such as the Sustainable Development Goals (SDGs), but the goals are no less challenging at an operational level. An important question for defining sustainability in an operational context is the most relevant timescale for measurement: can you define sustainability over a year? a decade? a century? longer?

In practice, much of our management of water occurs through the medium of long-lived infrastructure — infrastructure which can easily endure for a century or more (e.g., Li and Xu, 2006), even outlasting the financing and governance mechanisms that created that infrastructure (Hallegatte, 2009). At these timescales, decisions made today about design, allocation, governance, and operations may have impacts decades away, which is a timescale very relevant to the current period of climate change (Dominique, 2013). Indeed, climate change has been identified as a potential risk for water managers for some decades already, but extensive disagreement exists about how to best address climate as a risk (and opportunity). Since 2008, however, the level of discussion for water managers and planners has intensified as high-profile thinkers began to question the assumption that analyzing past hydrology is a sufficient means of understanding future water conditions (Milly et al., 2008; Wilby and Dessai, 2010).

Understanding the degree, form, and severity of climate risks facing water management and planning is necessary to achieve sustainable resource management and development goals for energy, food production, sanitation and supply, and ecosystems. Many authorities acknowledge that water is central to understanding human impacts from climate change (Sadoff and Muller, 2009), but widespread disagreement remains about where, when, and how climate change is important for water management decisions. Climate change is not relevant to all water management decisions, nor are climate change impacts equally significant when they do show an influence (Stakhiv, 2011). Beyond these basic truisms, however, little consensus exists around how we identify current and projected risks and then develop adaptive strategies that are robust to those risks.

These risks do not weigh evenly on all disciplines involved in water management. For decision making on aquatic ecosystems, for instance, the tolerance for qualitative over quantitative knowledge is relatively high; an awareness of how climatic trends are proceeding may be sufficient for environmental decision-makers in many cases. For infrastructure investments, however, quantifying risks is necessary for accurately meeting goals, especially if those goals have been defined through an economic or financial lens. Because water infrastructure is so necessary for meeting the demands of modern economies, much of the burden for constraining climate risks falls on engineers and engineering-informed positions.

In a simple sense, engineers build structures. These structures are often challenging to design and construct, expensive, and difficult to move, modify, or tear down. As investments, water infrastructure will often influence ecosystems, economies, and communities for very long periods, even outlasting their own operational lifetimes (Hallegatte et al., 2011).

This paper will provides insights into how climate change influences the work of water managers and planners, focusing on some recent approaches to identifying and responding to those risks.

2. The Significance of Climate Change: Uncertainty as a "New" Risk

Neither climate change nor uncertainty about the future are new to engineers or water managers. Indeed, the assumption that past water conditions were sufficiently accurate to describe future hazards and water availability (e.g., designing a levee to meet 1:100-year flood conditions based on 30 years of monitoring data) was known to be a "wrong" but useful approximation. Climate was assumed to be fixed or "stationary" (Milly et al., 2009, Wilby et al., 2009).

The water community has become uncomfortable with these assumptions, perhaps as the pulse of climate change has quickened in recent decades and climate scientists have felt more comfortable attributing the role of anthropogenic forcing to particular events. Certainly, the level of awareness of a potentially disruptive connection between climate change and water management has intensified. The appearance of new hydrological conditions, apparent shifts in climate variability and the widespread suspicion that many decades-old structures no longer match their current climate conditions appear to have fostered an increasingly wide dissatisfaction with longstanding approaches of quantitative analyses to support design, planning, and operations (e.g., Lins and Cohn, 2011).

Since the 1990s, climate models have been used as a tool to project the pace and extent of future climate impacts in order to inform more robust water management solutions. As a tool, downscaled climate models enabled a quantitative approximation of future climate. In many ways, these models allowed engineers to introduce new data without significantly changing how they designed and made management decisions.

However, the use of these models has proven controversial given their limitations in approximating the water cycle and in providing practical, high-confidence guidance. Discussions about the wise use of climate model information have often centered on how to reduce or constrain the uncertainties within and between models and scenarios. Technical discussions of "uncertainty" have often proven confusing and unhelpful to decision-makers seeking simple, plain-language technical recommendations. Hearing that models were unable to have consensus about increases or decreases in annual water availability may have even tainted the reputation of credible methods for incorporating climate information into water management decisions (Kundzewicz and Stakhiv, 2010, Brown and Wilby, 2012).

While future models and scenarios are likely to improve in their resolution and accuracy, many water managers and planners have found climate models dissatisfying for decision making when quantitative long-term outputs are necessary. Moreover, climate shifts on the water cycle will not simply alter design and operating specifications for availability and variability; climate change is already shifting many aspects of water demand as well. While bleached "bathtub rings" behind aging reservoirs and overtopped flood control levees may show how large changes in water availability can disrupt managed systems, there are also responses by water users that may have a comparable or even greater influence than direct climate impacts. Shifts from rainfed to irrigated agriculture, manufacturing to service economies, demographic shifts from immigration and shifts in reproduction and health, the rise of mega-cities, and population influxes from drying to wet regions may be among the easiest trends to predict, but all of these trends will interact in complex patterns. Together, the combination of direct and indirect climate impacts and socio-economic shifts has been called as "deep uncertainty" by some observers to reflect the challenge of making long-lived, high-impact decisions despite large knowledge gaps about future trends (Hallegatte et al., 2012, Walker et al., 2013).

The types of engineering approaches necessary for a well-understood, clearly-defined future would be quite different than those necessary for an "untrustworthy" future or even an unknown and unrecorded past (Brown, 2010). The widespread level of dissatisfaction among engineers, water managers, and decision-makers around the usefulness of projected climate information has led to two general concerns:

- how do we make long-term decisions about specific projects given deep uncertainty about the future of climate impacts in particular places; and
- how do we scale lessons from particular places and projects to ensure that climate information is appropriately mainstreamed within the design and operations of all engineered water management systems at an institutional level?

These two concerns differ from each other primarily in their level of analysis (individual project scale vs generalized decision-making processes): developing a single-project solution is not the same as ensuring that all projects initiated by a potentially large, diverse water management institution have successfully assessed and addressed climate risks. For the project scale, emphasizing the best, most appropriate, and effective practices is essential. At an institutional level, the approach should begin by examining how existing decision-making processes function and then modifying the most relevant steps in those processes to match successful project-scale methodologies.

3. Normalizing Climate Adaptation: Addressing Climate Uncertainty at Both Project and Institutional Scales

Formal engineering-based design processes for water infrastructure follow a similar structure and decision-making cycle globally. Using the US Army Corps of Engineers (2000) as a typical example, these steps usually include:

- Step 1 - Identifying problems and opportunities
- Step 2 - Inventorying and forecasting conditions
- Step 3 - Formulating alternative plans
- Step 4 - Evaluating alternative plans
- Step 5 - Comparing alternative plans
- Step 6 - Selecting a plan

Including climate information in a water management project should include two elements: the need to first assess the potential relevance of climate change to an existing or planned project in a way that realistically accounts for climate uncertainty and then to develop a strategy (or set of strategies) to reduce or avoid future identified climate risks. From a sustainability perspective, an ideal solution should also take account of ecological impacts and interactions. Recent methodological developments have led to the creation of a new framework that does just that.

4. Integrating Ecosystems into Long-term Water Management

Any credible definition of long-term sustainability should include ecological parameters. In recent decades, ecosystem consideration in infrastructure projects has typically occurred through environmental impact assessments, which often are relegated near the end of a design and planning process. There are few standard methodologies for these assessments, and their credibility is often questioned, particularly since projects are often well developed and difficult to modify at this stage.

The gaps between the disciplines of engineering and ecology around water management issues have been significant and durable, particularly around the translation of issues of ecological concern into an operational framework that can be evaluated using engineering-oriented performance indicators. "Ecosystem services" have been the most widespread approach to integrating ecological variables by assigning monetary values to functions supplied by ecosystems that are comparable to infrastructure functions such as water purification, flood risk reduction, and water storage (Sappelt et al., 2011). The development and assignment of economic value to ecosystem services is often challenging and may be overwhelmed by promised investment returns on planned infrastructure services. While ecosystem services have had some partial success, they have not proven to be a panacea (Schröter et al., 2014).

Recently, a team of ecologists and engineers developed a framework using decision scaling (eco-engineering decision scaling, or EEDS) as a basis for facilitating tradeoffs between infrastructure and ecological performance indicators in the context of climate resilience (Poff et al., 2016). Developed through support by the US National Science Foundation (NSF), EEDS defines performance indicators for both ecosystem and infrastructure without reference to economic valuation, ecosystem services, or other systems that attempt to translate ecological qualities within a finance or economic framework. Instead, EEDS establishes the water-climate criteria that can meet stakeholder or expert standards for success and failure and uses a stress-test approach to develop and compare green, hybrid and gray solutions for their impacts on ecosystems and water management needs.

EEDS is a powerful approach because it explicitly blends the needs and insights from diverse stakeholders and regulatory limits into a management tool that can quantitatively visualize tradeoffs between human needs and ecological performance under future climatic uncertainty. This occurs in the initial stages of planning and development rather than as a post-hoc "impact" assessment. Such early evaluation of ecosystem vulnerability is needed to reveal a range of potential design and management options in complex social-ecological systems.

5. The Five-Step EEDS Process

EEDS has been designed as a stakeholder-centered process mediated with technical inputs, which assumes that engagement with and service to stakeholders is critical to the ultimate success of adaptive resource management in a multi-institutional management context. The EEDS process has five key steps (Fig. 1). In practice, these steps are iterative, cycling back to step 1 for confirmation of technical work as the stakeholders themselves develop more insight into the process of defining long-term solutions and confront levels of risk tolerance. The first two steps involve defining a set of ecological performance indicators in the same terms as the relevant engineering indicators, with steps 3 and 4 (and 5, if necessary) comparing and evaluating approaches to balance and tradeoff risks and opportunities between ecological and engineering concerns

6. Applying EEDS in Mexico

The Alliance for Global Water Adaptation (AGWA) has begun collaborating with WWF-Mexico on analyzing the effects of climate change on environmental flows (e-flows) as they relate to Mexico's National Water Reserves Program. In terms of environmental protection, water reserves seek to provide legal support to ensure that the ecological flow is respected in selected basins that present high terrestrial and freshwater biodiversity and a low pressure on water demand.

Given the trend of economic development growth in the country, it is expected that for several of the basins in the water reserves program, the demand for concessions of water use will increase in the near

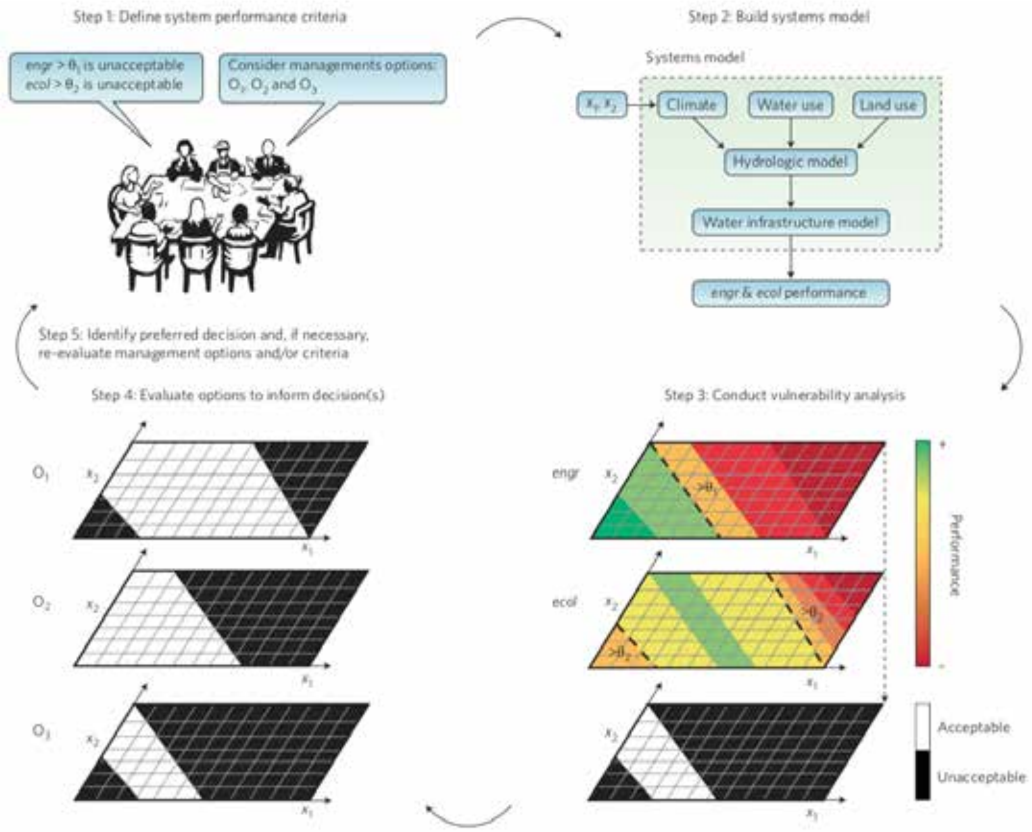

***Figure 1**: An overview of the process of eco-engineering decision scaling (EEDS). (Source: Poff et al., 2016).*

future, putting at risk the occurrence of the ecological flow and the provision of all its environmental services. In this sense, the degree of water reserves for environmental use represents a preventive instrument against the unsustainable use of the surface water in the country.

This project aims to quantify the climate adaptation benefits of the water reserves program in Mexico in order to demonstrate how environmental flows contribute to ecological and social resilience. The results of this work should be applied in the form of a tool or set of tools and methodologies that can guide national and regional CONAGUA staff in applying water reserves in basins throughout Mexico.

In this current project, seven pilot catchments (Fig. 2) are selected and used as case studies, identifying the vulnerabilities of their water resources allocation at the watershed level considering different drivers of change, including climate change and non-physical drivers, such as demographic growth, increased water demands and land use changes, among others. The bottom-up EEDS approach is followed, identifying current hydrological processes and analyzing their vulnerability under future scenarios. Those scenarios represent alternative development pathways for river basins that either establish protections of environmental flows (at various water reservation levels) or fail to implement water reserves. System responses are assessed by stakeholder-defined performance indicators that represent critical features, services, or threats to the system.

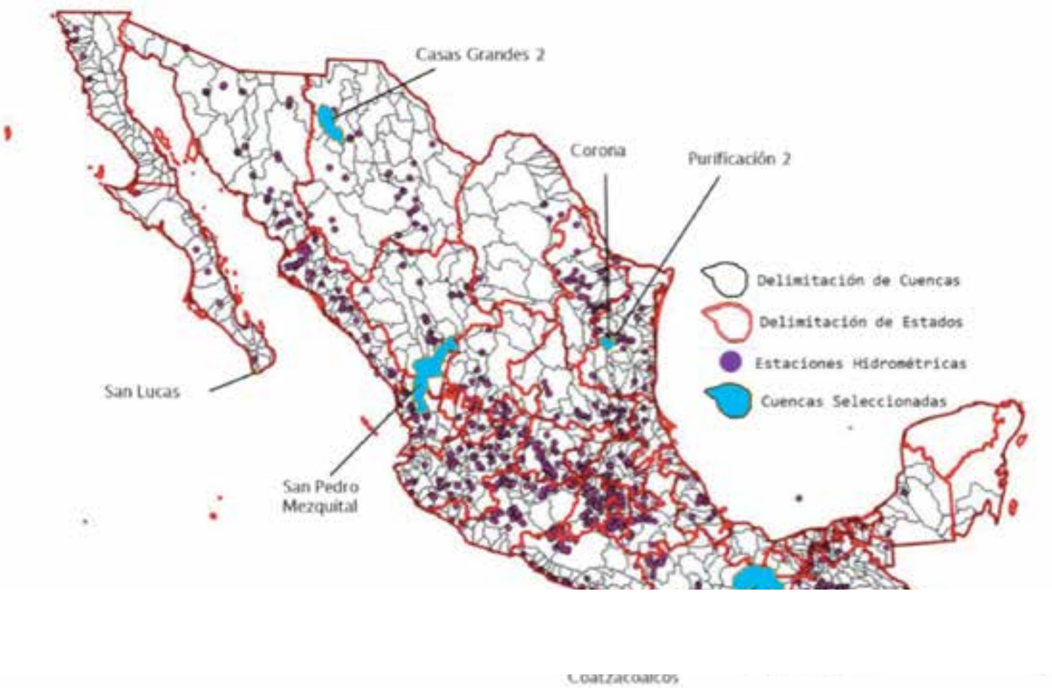

Figure 2: *The location of the seven selected pilot catchments*

This project is near its conclusion and a final report is being prepared. Results will be presented to CONAGUA, WWF-MX, and the Inter-American Development Bank. Using these early results as a proof of concept, the methodology applied in these case studies can be extrapolated to other watersheds or for the entire country, to allow an overall evaluation of the environmental water reserves, climate change projections and the impact of water demand in Mexico.

7. Embedding Ecosystems within Decision Making Processes: The CRIDA Framework for Climate Resilience and EEDS

EEDS as a process has also been embedded within a more comprehensive framework called Collaborative Risk Informed Decision Analysis (CRIDA), which is a decision support system developed by the Dutch Water and Environment Ministry, the US Army Corps of Engineers, SIWI, Deltares, UNESCO, and the Alliance for Global Water Adaptation to mainstream a new generation of resilient water management practices. Some six years in development with a global team of more than 100 contributors from a wide variety of disciplines, CRIDA is designed for technical water decision-makers who wish to assess and then reduce the influence of climate change on water resources management planning, design, and operations and combines state of the art approaches to develop robust solutions with stakeholders while assessing risk (decision scaling) with flexible and governance-sensitive approaches operations and implementation ("adaptation pathways"). EEDS can be seen as an application of the CRIDA approach by both setting main objectives and deriving a comprehensible set of performance metrics and thresholds (Mendoza et al., 2018). CRIDA builds on existing approaches to technical water management decision making processes, inserting direction for aspects relevant for resilient actions.

8. Conclusion

A key continuing challenge for rational water resource management is to provide a practical approach to assist planners and decision-makers in navigating complex problems and diverse interest groups who are confronted by uncertain and changing conditions. As effective adaptive decision-making is most likely to succeed where stakeholders are fully engaged, we believe the EEDS offers the potential to serve as the foundation of a new management platform that advances freshwater sustainability while meeting human needs for water. Further refinement could include how to accommodate future changes in societal cost functions (for example, due to population growth) and shifts in ecological requirements under transient climate and socioeconomic conditions, as well as how to sequence management actions in a fashion that promotes long-term success. Managing the future will necessarily occur in an adaptive context; therefore, equally robust monitoring and evaluation plans will be needed to ensure that decisions are drawing upon the best available information when evaluating the consequences of alternative decision options and management strategies.

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