Climate Change and Water Resources Adaptation: Decision Scaling and Integrated Eco-Engineering Resilience

Over the course of the last hundred years, tens of thousands of dams have been built, profoundly modifying global hydrological systems.[1,2] These dams were designed to last for decades to centuries with fixed operational rules to maximize energy production, irrigation and urban supplies, or storage and diversions. However, meeting human demands has come at great expense to the "natural" aquatic and riparian ecosystems that evolved in these hydro-systems, contributing to degradation of biodiversity and associated ecosystem services.[3,4] In the 21st Century, sustainability has become central to "green growth" and economic development, particularly in regions facing intensive water infrastructure development. However, the connection between *sustainable* water resources management (WRM) and climate change has raised new concerns about impacts on ecosystems as well as infrastructure design and operations, particularly given the pace of climate change and the uncertainty associated with Global Circulation Model (GCM) projections.[5] Perhaps even more challenging is bridging engineering- and ecosystem-based definitions of sustainability given a shifting hydrological baseline. A fundamental question for sustainable WRM is: **Can we simultaneously achieve resilient infrastructure and resilient ecosystems in basins** as varied as the Mekong (130 planned large dams),[6] the Himalayas (>300)[7] or the Andes (>150)[8]?

Ecosystems are functionally dynamic and comprised of adaptive agents, but water infrastructure is generally static, with a specified reliability that rests on the assumptions of a stationary climate.[5,9,10] Climate change forces WRM players (planners, engineers, conservation ecologists, economic investment institutions) to reformulate stationary paradigms into flexible strategies grounded in shifting eco-hydrological realities.[11,12] The present period of re-thinking sustainable WRM presents a genuine opportunity to incorporate ecological principles into new infrastructure *from the beginning*.

Two promising developments facilitating such integration have very recently emerged. First, a new engineering perspective called "Decision Scaling" shifts the process of assessing water resources vulnerability from top-down GCM-based analyses to a bottom-up, risk-based approach. *The **goal** of Decision Scaling is to engage decision makers directly by starting with the defined decision metrics, and then evaluating the evidence based on consequence of failure and confidence in the data* (Fig. 1). This process links vulnerability of specific infrastructure failure conditions (e.g., not enough water to bring a crop to harvest) with a variety of non-stationary threats, such as climate, demographic, and economic shifts or urbanization.[13-15] With the "end of reliability,"[9] Decision Scaling allows adaptive design and management to shift to a process approach on timescales relevant to operational lifetimes and flexible under changing climate.

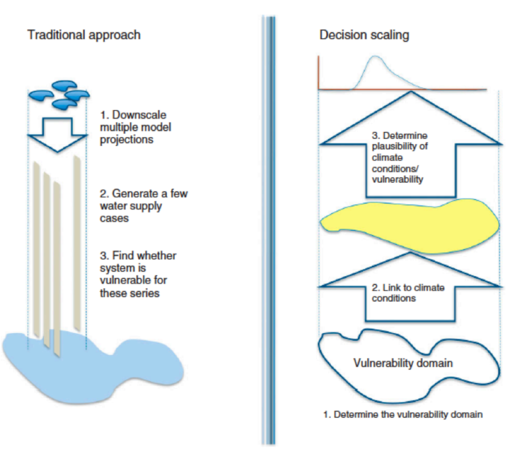

Figure 1. Decision scaling showing contrast with "top-down" approach[12,13]

The second promising development is institutional and cultural. A coalition of global decision-making members of the water community are coalescing around the need to bridge institutional and disciplinary divisions to develop a Decision Support System (DSS) capable of integrating existing tools and data sources to aid water managers, investors, and policymakers in systematically incorporating climate adaptation approaches to WRM. Led by the World Bank and Conservation International (J. Matthews, this proposal), the DSS collaborators span multilateral development banks, governments (city, national, UN), researchers (agencies, universities), NGOs, and the private sector (see SESYNC participant list and full list at alliance4water.org). Total annual WRM investments from AGWA members are in excess of 20 billion USD. The DSS encompasses hydro-climate, economics-finance, engineering-ecology, and governance working groups, and *all four teams agree that formalization of Decision Scaling* is the best vehicle for infrastructure design and operations, and that sustainable ecosystem management is a core ethic. Large-scale projects have been implemented in North America recently[16] and more are in process in Asia through the US Army Corps of Engineers.

Our **overarching goal in this project** is to develop a "conceptual-application decision framework" that explicitly incorporates aquatic ecosystems into the "vulnerability domain" (Fig. 1) of Decision Scaling and thus "mainlines" aquatic ecosystem sustainability into the broader DSS that will guide policy and investment in WRM. *This is inherently a synthetic process in that we seek to find new solutions among historically antagonistic and competing disciplinary approaches (engineering, ecology) to "sustainable" water management.* Unfortunately, many of the governance and investment institutions (e.g., World Bank) that have bought into the AGWA vision are less discerning about the role of ecological theory than engineering. We view SESYNC as an ideal venue to bring together thought leaders in river engineering and ecology to formally develop a scholarly eco-engineering decision framework for a ready, actionable audience. Thus, our proposal asks: **How can we integrate ecological resilience within infrastructure Decision Scaling?** We aim to create an integrated, operational approach to dynamic ecology-engineering that will be suitable for the DSS to inform sustainable WRM. Through AGWA, we have already aligned a set of global and regional implementation partners willing and ready to turn our outcomes into reality as "pilot" projects at both planning and local resource management scales.

The ecological foundation for resilience acknowledges the *enormous spatial and temporal heterogeneity of water*. Water infrastructure is generally designed to diminish this heterogeneity in favor of reliability. The structure and function of aquatic species and "natural" ecosystems are also strongly shaped by this natural heterogeneity, particularly the climatically driven temporal variation in flow regime.[17] Through the construction and operation of water infrastructure, humans are homogenizing regional scale variation in historical flow regimes, with significant implications for freshwater biodiversity and ecosystem resilience.[18] Climate change will likely modify and/or amplify this spatial-temporal heterogeneity, perhaps in novel, hard to predict ways (e.g., no-analog states[19]) Given future hydrological uncertainty, a decision tool that integrates water infrastructure and ecosystem resilience must balance local-regional context with an evolutionary ecological understanding of vulnerability to guide risk-based decision-making.

We envision a four-step process to be realized through workshops: (1) define/integrate ecological resilience in an engineering Decision Scaling framework, (2) translate this definition into a vulnerability assessment protocol, (3) link this definition and protocol to data products for regions with limited hydrological records, and (4) amplify these connections to key implementing partners/projects.

A key initial objective of this project is to define and *operationalize* the idea of river ecosystem resilience. This will allow for vulnerability analysis and risk assessment that can feed into a sustainable WRM decision framework. We propose that freshwater resilience is a place-based construct that has both a social dimension (What do we "want? Will we pay for it?) and a natural science dimension (What bio-climate-physical factors define the boundaries of different potential ecosystem states?)[20].

"Resilience" is a long-standing idea in ecology[21] and in social-ecological systems theory (see resalliance.org). Generally, resilience refers to the capacity of a system for renewal, but variations occur: the ability of an "ecosystem state" to resist exogenous disturbance, the ability to return to such a state following disturbance, or mediating transitions between multiple stable states.[22] The basic concept is widely embraced, but resilience comprises many nuanced concepts: resistance, disturbance, sensitivity, exposure, evolutionary history, heterogeneity, precariousness[23] (see resalliance.org).

In a water resources context, "resilience" is often conflated with reliability or efficiency.[9] Therefore, from a strictly engineering perspective "resilient" WRM need not include ecological principles, pointing to the urgent need for **scientists, engineers, and managers to integrate their perspectives of "resilience"** if we are to achieve a coherent operational definition that can inform truly sustainable WRM**.** This is not trivial; sustainable WRM must be grounded in eco-hydrological dimensions and respect the role that climate variability and climate change have in altering those dimensions. Thus, a *scholarly activity* within the SESYNC project is to develop a common perspective on resilience to inform sustainable WRM.

However, "resilience" presents a concept/praxis contradiction. *In theory*, ecology acknowledges that ecosystems shift and transform over evolutionary timescales, with climate change a significant driver. *In practice*, freshwater conservation often assumes a rather static view by "restoring" systems to some past "reference" state.[24] Management guided by restoration is challenged because *both hydrological and ecological references are moving targets* due to extensive past/present human modifications of the landscape, including non-native species.[24,25] Restoration to the past need not promote future resilience.[5,26]

We view SESYNC as a convener to guide river conservation ecology in transition from a largely static restoration perspective to a more dynamic resilience perspective, to blend insights from practitioners, data hubs and academia, and to focus on critical challenges.[26] **We propose to advance this transition by uniting the engineering perspective of Decision Scaling with the ecological science and management philosophy of "Environmental Flows."** Eflows builds on basic ecological theory and *is grounded in the understanding that eco-hydrological relationships have a spatially variable context that relates differences in temporal disturbance regime* (magnitude, frequency, timing, predictability) to regional climate.[27,28] Analysis of river discharge records allows classification of disturbance regime "types" at regional to continental scales[29,30] and these have discernable ecological differences.[31] Thus, altering "historical" flow regime induces ecological change[32] relative to the flow regime type. For example, stable (unvarying) groundwater-dominated systems are more sensitive to a management that imposes abrupt fluctuations in flow (say, a hydroelectric dam) than "flashy" rainfall-response systems. Accordingly, the sensitivity of particular ecosystems will be conditioned by how much change in key hydrological components (e.g., frequency, timing) occurs relative to the historical range of variation in flow.[33,34]

Eflows science (and the advances in eco-hydrological process understanding it subsumes) provides the theoretical and empirical basis to inform place-based "resilient" WRM in a general, spatially-explicit context, from individual structures to entire river basins. The match between Decision Scaling and Eflows is rich with potential, because Eflows shares the philosophy of striving to engage stakeholders to define "thresholds" of vulnerability and risk in the context of infrastructure.[27,28] Of course, data available to inform any particular vulnerability analysis will be variable (or have different degrees of "confidence"), which is why we should work with data hubs such as CUAHSI, NOAA, WMO, and NASA to facilitate work in areas with limited river discharge` records. We believe this pathway leads toward more sustainable WRM, particularly for river basins and countries where scores to hundreds of new dams are being proposed and where the lack of fine-grained hydrologic and ecological data too often prevent the application of extant approaches (e.g., Integrated Water Resources Management[35]) from being incorporated into sustainable water infrastructure design and management.

Workshop 1: Building "Resilience" as a Concept: Ecosystems and Infrastructure

The first workshop will convene some of the leading proponents of engineering decision scaling, flow-centered freshwater conservation, and freshwater adaptation. The goal for the workshop is building a

conceptual framework for resilient water resources management using a dynamic, non-stationary vision of eco-hydrological sustainability from unified ecological and engineering water resources management viewpoints.
Product/Metric: A perspectives publication on the application of freshwater resilience in a WRM context

Workshop 2: Assessing Vulnerability: Decision Scaling across Engineering and Ecology

The second workshop should build on the first and would focus on the mechanics of transferring the unified concept of freshwater resilience into a decision-scaling framework by developing protocols for conducting vulnerability analyses of conjoined water engineering and ecological resilience. How would vulnerability analyses for different sectors be conducted? How do we identify the "actionable time scales" over which future vulnerabilities are assessed and water infrastructure is operated? How would we frame this so that individuals, institutions, planners, and resource managers could navigate through these issues?
Product/Metric: A publication on risk assessment for dams and ecosystems given a non-stationary climate

Workshop 3: Operationalizing: Connecting Tools to Managers

For the developing world, long-term data records are often patchy or scarce, yet emerging economies are often the locus of high levels of biodiversity as well as rapid infrastructure development. The third workshop would define/build data products linked to our resilience-vulnerability framework. The WMO and NOAA have been seeking a connection with water managers through "climate services" (particularly the WMO's "Water Exemplar" in the Global Climate Services Framework), while CUAHSI and NASA's Applied Science division have been working more explicitly on water resources relevant to climate adaptation (e.g., evaluating snowpack meltwater equivalent for seasonal water management forecasts). Can we embed these data products within an integrated decision-scaling framework to evaluate risk?
Product/Metric: Integration with global hydro-met services/tools, connecting data sources/products from these data product partners

Workshop 4: Synergies for Amplification and Implementation

The Alliance for Global Water Adaptation network (AGWA; alliance4water.org) is constructing a decision support system (DSS), and connecting the ecology-engineering component of this work (workshops 1-3) to the economics-finance, hydro-climate, and governance streams of AGWA would be a powerful means of amplification. With AGWA, the final workshop will focus on transitioning the results of previous workshops to amplifying messages beyond our working group and into other critical targets within the water community, particularly multilateral groups (such as development banks [World Bank, IDB, ADB, KfW, EiB], capacity building organizations [GiZ], aid agencies [US AID, JICA, Sida, SDC, Dutch Foreign Ministry], and intergovernmental vehicles with a *clear policy potential* to support sustainable water management [GEF, UNFCCC]).
Product/Metric: Working with global/national agents of change to move to implementation

In general, for this project we will use a **synthetic approach** that combines strengths of both engineering and eco-hydrological approaches, integrates a coherent definition of resilient water resources management, and has a systematic basis to modeling that can serve to define decision-making processes.

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