# Is Resilience Achieved in Colorado River Recovery Programs? A Complex Social-Ecological Systems Approach

by

Jaishri Srinivasan

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Graduate Supervisory Committee:

Michael Schoon, Co-Chair
John Sabo, Co-Chair
Dave White
Marco Janssen

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ABSTRACT

Globally, rivers are being heavily dammed and over-utilized to the point where water shortages are starting to occur. This problem is magnified in arid and semi-arid regions where climate change, growing populations, intensive agriculture and urbanization have created tremendous pressures on existing river systems. Regulatory incentives have been enacted in recent decades that have spurred river restoration programs in the United States. But what kind of governance does river restoration require that is different from allocative institutional set-ups? Are these recovery programs succeeding in restoring ecological health and resilience of the rivers? Do the programs contribute to social-ecological resilience of the river systems more broadly? This study aims to tackle these key questions for two Colorado River sub-basin recovery programs (one in the Upper Basin and one in the Lower Basin) through utilization of different frameworks and methodologies for each. Organizational resilience to institutional and biophysical disturbances varies, with the Upper Basin program being more resilient than the Lower Basin program. Ecological resilience as measured by beta diversity (for the Upper Basin) was a factor of the level of hydrological and technological interventions rather than an occurrence of the natural flow regime. This points to the fact that in a highly-dampened and managed system like the Colorado River, the dampened flow regime alone is not a significant factor in maintaining community diversity and ecological health. A broad-scale social-ecological analysis supports the finding that the natural feedback between social and ecological elements is broken and recovery efforts are more an attempt at resuscitating the river system to maintain a semblance of historic levels of fish populations and aquatic processes. Adaptive management pathways for the future need to address and build pathways to transformability into recovery planning to achieve resilience for the river system.

## DEDICATION

This work is dedicated to the memory of my maternal grandmother, whose kindness and compassion will live on in my heart; my maternal grandfather, whose stories I grew up listening to and who inspired me with the capability to tell the stories I have told in this manuscript; and my father, who paved the road for me to get here.

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# INTRODUCTION

Longstanding approaches to solve ecological and social problems are often insufficient to address complex, highly interactive challenges facing natural resource governance today. Climate change, species loss, non-point source pollution and technological and population pressures on scarce resources are examples of problems that arise in social-ecological systems (SES) (Koontz, et al., 2015). In an era of rapid global and climate changes, scholars have argued for establishing more “adaptive” forms of natural resource management to build resilience in social-ecological systems (Holling, 1978). More ambitious scholars have called for adaptive water governance (Pahl-Wostl, 2007); (Huitema, et al., 2009), where adaptive governance refers to increasing the capacity of whole social-ecological systems to turn changing conditions and perturbations into an opportunity to re-organize internally and shape the direction of change into a new system state that is environmentally, socially and economically desirable (Folke, et al., 2005).

While exogenous factors might account for some variation in collaborative water resource governance across states, river basin organizations (RBOs) themselves can be expected to determine, to a considerable degree, whether and to what extent they will be successful (Schmeier, 2014). Increasingly collaborative governance models are being worked at various scales from local watersheds and regional bays to large river systems, many of which involve local partnerships, watershed councils and river conservation initiatives (Gerlak & Heikkila, 2006). Environmental change such as variability in water availability, extreme events like floods or droughts, or water pollution pose serious challenges to effective management of shared water resources. (Schulze & Schmeier, 2012) found that the inclusion of adaptation mechanisms contributes to ensuring river basins' resilience to environmental change while the lack of RBO internal adaptation mechanisms (including factors such as membership structure, functional scope and information sharing) can hamper resilience and threaten sustainable development.

Resilience is an essential factor in social-ecological systems faced with uncertainty and surprise and is defined as the amount of disturbance a system can absorb and still remain within the same state or domain of attraction (Holling, 1973). Resilience also encompasses the ability for reorganization and renewal subject to disturbance and change. Freshwater systems have an essential role as the bloodstream of the biosphere but the dominant management paradigm is that of "command and control" centralized management with considerable disconnection from learning and recognition of hydrological and ecological dynamics (Folke, 2003). There is a need to develop stewardships that interpret and respond to environmental feedback, and that support flexible organizations, institutions and adaptive management processes in a manner that enhances the resilience of social-ecological systems (Folke, et al., 2003).

The aim of this dissertation is to utilize a complex social-ecological systems and resilience lens to assess the state and performance of sub-basin scale river recovery programs, with a special emphasis on the Colorado River system in the United States Southwest. The river recovery programs are a unique case-study because they are situated in the nexus of social and ecological elements with both governance and ecological outcomes being central to program governance. The unique institutional architecture of the programs elicits a study in how to make them sustainable, by analyzing the factors that ensure longevity and resilience in the face of institutional and ecological shocks. Furthermore, ecological resilience assessment is also central to the study, because anthropogenic and climate change pressures have vastly limited the scope of what is possible to ensure a healthy and ecologically integral river system.

The following sections summarize the contents of the three central parts of this dissertation and provide a summary of the questions, methods and outcomes in each section. The two programs that are the main focus of this dissertation include the Upper Colorado River Endangered Fish Recovery Program (UCR-EFRP) and the Lower Colorado River Multi-Species Conservation Program (LCR-MSCP).

**Part I: Characterizing Organizational Resilience to Institutional and Biophysical Disturbances**

This study characterizes resilience of organizations undertaking river basin governance and recovery. The Upper Colorado River Endangered Fish Recovery Program (UCREFRP) and the Lower Colorado River Multi-Species Conservation Program (LCR-MSCP) are defined in this study as “polycentric super-organizations”. This study matches two frameworks – an environmental disturbance-organizational response framework and a trust ecology framework to characterize organizational resilience – and uses attitudinal diversity (characterized by attitudes towards agendas) as the mediating metric between the two. Environmental disturbances are either press or pulse and either institutional or biophysical in nature. Four types of trust are defined – dispositional, rational, affinitive and procedural. Trust richness is characterized by the number of different types of trust in a network and trust evenness is the relative abundance of trust types within the network. Four types of attitudinal diversity metrics are utilized – supportive, clarifying, conditional and critical. The results indicate that increased attitudinal diversity in the formative years of both programs indicate the prevalence of rational and procedural trust. The more long-lasting UCREFRP displays lower attitudinal diversity over time, with increasing trust richness and evenness, making it strongly resilient to disturbances. The LCR-MSCP, conversely, ranks low on both trust richness and evenness making it weakly resilient to disturbances.

**Part II: Assessing Ecological Resilience and the Effectiveness of Adaptive Management: A case study of the UCR-EFRP**

This study analyzes a pioneering program in river basin recovery at large sub-basin scale – the Upper Colorado River Endangered Fish Recovery Program (UCREFRP). The program seeks to mitigate for and balance use on the river system with preservation of critically endangered fish species using adaptive management approaches. The study assesses the effectiveness of the program actions first and the adaptive management paradigm in this context second using mixed qualitative and quantitative approaches. Assessment of program effectiveness utilizes annual flow regime variability, and year-by-year summation of categories (hydrological, technological, ecological) of management interventions as predictive variables of abundance-based beta diversity indices of fish communities in six key Upper Basin river sites. Assessment of the program actions against the adaptive management paradigm uses a Resistance-Resilience-Transformation (RRT) scale. Results show that fish community beta diversity metrics are most responsive to hydrological and technological interventions, though overall effectiveness is predicated on long-term ecological interventions designed to provide favorable biotic environments for endangered species. Assessment of the effectiveness of the adaptive management paradigm shows that program policies and actions need to account more for compounded effects of multiple environmental and anthropogenic stressors to maintain the ecological health of the river into the future.

**Part III: A Social-Ecological Systems Level Clinical Diagnosis of Colorado River Sub-basin Recovery Programs**

With a particular emphasis on the Upper Colorado River Endangered Fish Recovery Program (UCREFRP) and the Lower Colorado River Multi-Species Conservation Program (LCR-MSCP), this study analyzes, for each program, four system properties that contribute to resilience - system architecture; assemblage of system elements; social and natural capital flows; and system renewal and continuation. Each of these system properties is analyzed based on specific social and corresponding biophysical indicators. The system properties are then ranked on a carefully constructed scale based on gradations of each system property (derived from literature) on both social and biophysical indicator standing. The difference in results illustrate the feedbacks and trade-offs that occur in the programs between the social and biophysical components. This approach is novel in that, firstly, it brings ecological/biophysical indicators to the forefront and make them an equal part of the social-ecological system assessment as opposed to a small part. Secondly, the ranking is based on holistic system properties that have been proven to be measures of resilience as opposed to indicators that may give a partial view of the system. Third, the distance in ranking between social and biophysical indicators is proposed as a "zone" where the strength of the feedbacks between social and biophysical components as well as the trade-offs play out.

PART I: CHARACTERIZING ORGANIZATIONAL RESILIENCE TO INSTITUTIONAL AND BIOPHYSICAL DISTURBANCES

## 1. Introduction

Large rivers in arid regions that have been intensively developed through dam building and diversions have incurred a high ecological cost that has seldom been well understood or factored into decision-making (Pfister, et al., 2009). Rivers running through arid and semi-arid landscapes are among the most over-allocated resources resulting in a plethora of common problems across the globe including concerns of sufficient water availability to sustain burgeoning urban and industrial growth and intensive agriculture, water security concerns during drought conditions due to the impacts of climate change and increased salinity and water quality degradation from agricultural runoff. Several arid land rivers such as the Colorado River in the Southwest United States are so severely strained and so heavily engineered that they no longer run to the sea thereby disrupting natural hydro-geological processes in addition to increasing water stress.

In the face of these issues, the maintenance of river health has become increasingly urgent. There has been increasing concern in recent decades on rehabilitation of river systems to ensure they continue to maintain essential ecological processes such as a healthy, functioning aquatic ecosystem as well as supporting a functional riparian ecosystem even while land use changes press in. In the United States, new institutions specifically for river restoration and stewardship have begun proliferating over the past couple of decades. The primary drivers have been the necessity of compliance with the Endangered Species Act of 1979 and public mobilization of political support to preserve the ecosystem services the river provides. With the creation of such institutions also comes the question, can these institutions sustain themselves over the long-term? What would keep them going despite changes occurring internally and disturbances from the environment externally?

Much of natural resource management has been an effort to control nature in order to harvest its products, reduce its threats and establish highly predictable outcomes. This has resulted in dampening extremes of ecosystem behavior to a high degree through, for instance, flow stabilization by dams in previously wildly flooding or "flashy" southwestern US rivers resulting in native fish fauna that is less resilient in the face of invasive species and shrinking the range of native species to free-flowing rivers. Institutionally, control is manifested in bureaucracies which implement variance reduction and promote conformity by discouraging innovation or behavioral variance, consequently making them significantly less resilient to internal and external disturbances (Holling & Meffe, 1996).

Long-term institutional analysis, especially institutions for managing natural resource use or allocations have been subject to extensive study resulting in multiple diagnostic frameworks (Ostrom, 1990); (Anderies, et al., 2004); (Ostrom, 2011); (Ostrom, 2009). The dominant paradigm of environment as a consumer falls short when the environment itself (both biotic and abiotic contributions) is a fundamental precondition to the existence and vitality of the resource, as in rivers and streams. Furthermore, significant literature and theories have been developed toward adaptive governance (Huntjens, et al., 2011); (Huntjens, et al., 2012), complexity governance (Pahl-Wostl, et al., 2010) and social learning in water systems (Pahl-Wostl, 2009); (Johannessen, et al., 2019).

Arguments have been made that institutional scholarship has become overly concerned with explaining institutions and institutional processes, notably at the level of the organizational field, rather than with using them to explain and understand organizations. There is considerable fluidity and confusion on the boundaries between institutions and organizations. Organizations are embedded in an institutional context of socio-cultural ideas and beliefs that prescribe appropriate and socially legitimate ways of doing things and are therefore subject to institutional influences in either positive or negative ways (Greenwood, et al., 2014).

This study examines the effect of both biophysical and institutional disturbances on organizations through a study of the extent of attitudinal diversity in response to organizational agendas. These are matched to the types of trust that results from intra-organizational collaborative processes over time and how these translate to resilience for institutions that govern river restoration particularly in the United States Southwest. Attitudinal diversity is defined as the varying attitudes around the yearly program agendas, ranging from supportive to critical. Trust richness is defined as the number of different trust types within a network, while trust evenness refers to the relative abundance of trust types within a network.

The cases include the Upper Colorado River Endangered Fish Recovery Program (UCREFRP), and the Lower Colorado River Multi-Species Conservation Program (LCR-MSCP). For the purposes of this study, the two programs are a 'super-organization' because they represent a polycentric organizational construct with multiple organizations working toward a common goal. The study answers the following research questions:

***(1) How does attitudinal diversity vary over time and what is the role of different trust types in intra-organizational collaborative processes?***

***Prosposition 1:*** Time will neutralize, or make less important, the effects of deep-level or attitudinal diversity.

(2) ***How do institutional responses to various disturbances characterize institutional resilience?***

***Proposition 2:*** In long-term institutions, resilience is fostered by high levels of trust richness and trust evenness evolving over time.

Because this study makes a distinction between institutions and organizations, the next sections will focus on a conceptualizing organizational resilience by drawing from organizational science and resilience theory and subsequently, a decomposition of diversity constructs. This is followed by a typology of trust types at play in intra-organizational collaborative processes. Finally, a framework is utilized to describe how the ecology of the distribution of trust types can be utilized to characterize organizational resilience in the face of environmental and institutional disturbances with the above-mentioned case study examples.

Because a disturbance-response framework is utilized in the conceptualization of organizational resilience, a characterization of the types of disturbances hitting the systems being studied is detailed. Disturbances, in an ecological sense, are defined as any relatively discrete event in time that disrupts ecosystem, community or population structure and changes resources, substrate availability, or the physical environment (Pickett & White, 1985). There has been a growing emphasis in social-ecological systems science that complex dynamics often lead to unexpected outcomes with long-term effects. The disturbances that occur in social-ecological systems can be sudden events that are large in magnitude and/or infrequent, termed as "pulse" dynamics or extensive, pervasive and subtle change termed as "press" dynamics (Collins, et al., 2011). Furthermore, institutional disturbances as utilized in this study can be those rooted in broad socio-cultural norms and values, legislative and regulatory measures or market factors, while the biophysical disturbances refer to cases of episodic “hydrologic” drought, climate change and continuing chronic “megadrought” as well as the presence of invasive species.

## 2. Organizational Resilience Conceptualized

Organizational resilience, in essence, is defined as the maintenance of positive adjustment under challenging conditions (i.e. shocks, disruptions, stresses and strains) such that the organization emerges from those conditions strengthened and more resourceful (Vogus & Sutcliffe, 2007). In other words, the process of ‘resiling’ in the face of ongoing strain and discrete jolts is due to the presence of latent resources that can be activated, combined and recombined in new situations as challenges arise. The implication is that resilience relies upon past learning and fosters future learning, but also exists independently of learning and is embedded within a broader store of constitutive capabilities or endowments (Vogus & Sutcliffe, 2007). These characteristics correspond with the three dimensions of organizational response resilience not only to current issues (concurrent action) or the past (reactive action), but also to the future (anticipatory action) (Duchek, 2014).

Furthermore, past learning speaks to a reliance on organizational memory that is posited to consist of mental and structural artifacts that have consequential effects on performance (Walsh & Ungson, 1991). Anticipatory capabilities refer to the ability of organizations to detect critical developments and to adapt proactively to future changes before they happen. This involves activities such as looking for signals or environmental scanning, which is a process of acquiring information in preparation for inevitable surprises (Duchek, 2014). Both anticipatory learning and organizational memory are rooted in actors’ various capabilities, knowledge skills, processes and routines that facilitate access to resources.

Capabilities for durability, which is another feature of organizational resilience, refers to the endowments actors possess prior to adversity that shape their capacity for positive adjustment. Endowments facilitate resilience by enabling adaptability and may include financial capability, cognitive capability, behavioral capability, emotion-regulation capability and relational capability endowments (Williams, et al., 2017). This speaks to resilience at the organizational level referring to an organization's ability (embodied in the existence of resources, ideologies, routines and structures) to absorb a discrete environmental jolt and restore prior order. (Williams, et al., 2017). The authors also speak of an extension of this concept in the systems tradition to include dynamic processes rooted in relational patterns between actors that may effect a reorganization following a disturbance, while still retaining essential structures, functions and identity.

Laughlin (1991) argues that organizations, for possible psycho-social reasons are naturally change resistant, with a strong tendency to "inertia" and will only change when forced, 'kicked' or disturbed into doing something. However, once disturbed, he argues that the track which the disturbance takes through the organization and the degree of transformation it will generate in the pathway it follows will differ over time and across different organizations based on certain organizational characteristics. These organizational characteristics comprise three distinct elements: sub-systems (tangible elements such as buildings, people, machine etc.), design archetypes (intangible structures, accounting processes and systems) and interpretive schemes (core values, norms, culture, beliefs, rules, missions statements etc.), with the less tangible elements being more central to organizational functioning (Laughlin, 1991).

Laughlin (1991) described four pathways that characterize organizational responses to environmental disturbances:

(1) Rebuttal – the environmental disturbance is externalized and/or deflected in an attempt to protect and maintain the prevailing organizational equilibrium. These involve negligible changes to the sub-systems, design archetypes and interpretive schemes.

(2) Reorientation – If a disturbance cannot be rebutted by adjusting the internal organizational infrastructure, it is accepted and assimilated within the workings of the organization in such a way that it is absorbed by interpretive schemes, with lasting change to the nature of the design archetype and some elements of tangible sub-systems.

(3) Colonization – It is forced upon the organization by those who have power over the design archetype and its resources, leading to major shifts that create lasting and fundamental change in both the visible and invisible elements.

(4) Evolution – Also involves major changes to the organization and its interpretive schemes, with the difference being, the change is chosen and accepted by all organizational participants freely, without coercion. It leads to a change in the current interpretive scheme which will also drive changes in the design archetype.

Intrinsic to these models is the distinction between the first and second-order change precipitated by environmental disturbances that has parallels to single and double-loop learning (Argyris & Schon, 1978). First-order rebuttal and reorientation pathways are responses to morphostatic change (making things look different while remaining the same) and are therefore termed 'transitions', whereas second-order changes including colonization and evolution are morphogenetic (penetrating deeply into the genetic code) and represent ‘transformations’.

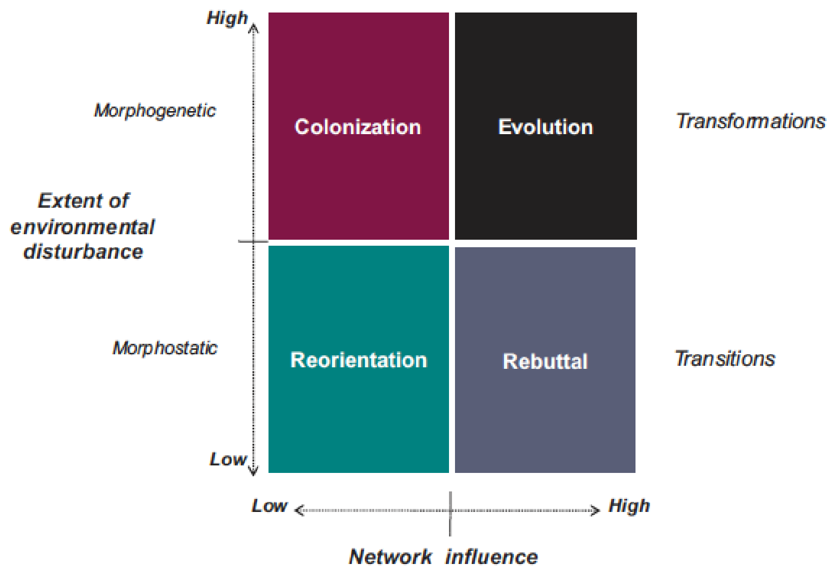


**Figure 1. 1:** Reconstructed Model of Laughlin's Organizational Change Pathways (Tucker, 2013).

What kind of organizational response is invoked and what pathway is chosen is dependent on the extent of the environmental disturbance, which can range from low to high. Figure 1 shows the organizational response patterns in relation to environmental disturbances (Tucker, 2013).

## 2.1 Conceptualizations of Diversity

Diversity in social-ecological systems comes in different shades and sizes including functional diversity, livelihood diversity, cultural diversity, and the relative size or power of these groups. Diversity and redundancy in social–ecological system components such as species, landscape types, knowledge systems, actors, cultural groups or institutions provide options for responding to change and disturbance and for dealing with uncertainty and surprise (Folke, Colding, & Berkes, 2003; Ostrom, 2005; Kotschy et al., 2015).

Diversity is often used to describe the distribution of differences among the members of a unit with respect to a common attribute. Diversity and heterogeneity has often been used interchangeably, though heterogeneity implies interactively integrating different entities whereas diversity implies divergence (Shavit, et al., 2016). There has been no consensus in the literature on the effect of heterogeneity and group size on collective action due to lack of uniform conceptualization of these factors (Poteete & Ostrom, 2004). For instance, one study predicted that diversity in teams would lead to less liking and lower affective outcomes (Byrne, 1971) (Milliken & Martins, 1996); another study found that declining levels of organizational commitment occurs when diversity in gender and race increased with no negative effects for age, education and organizational tenure (Tsui, et al., 1992); a third study found that heterogeneity in age and tenure was positively related to turnover, but tenure diversity has also been positively related to internal task processes and finally that functional diversity was positively related to external communication but the direct effect of diversity on team performance was negative (Ancona & Caldwell, 1992).

Theoretical and empirical research suggests that response diversity in combination with functional redundancy is important in maintaining ecosystem services in the face of disturbance and ongoing change and increasing system resilience (Kotschy, et al., 2015). Typologies of organizational diversity can reflect *separation*: team members hold opposing positions on a task- or team-relevant issue; *variety*: team members bring a multiplicity of information sources to bear on an issue; or *disparity*: one member of the team is superior to the other members in resources or status (Harrison & Klein, 2007). Stirling (2007) categorizes diversity typologies based on differing contexts including:

(1) ***Variety***, which is seen as the number of categories into which system elements are apportioned. "*All else being equal, the greater the variety, the greater the diversity*"

(2) ***Balance***, which is a function of the pattern of apportionment of elements across categories. "*All else being equal, the more even the balance, the greater the diversity*" and

(3) ***Disparity***, which refers to the manner and degree in which the elements may be distinguished. "*All else being equal, the more disparate are the represented elements, the greater the diversity*".

The idea of diversity as separation is rooted in similarity attraction and social categorization theories which argue that greater similarity yields higher levels of cooperation, trust and social integration. Conversely, members who differ markedly on a continuum will experience low cohesion, high conflict, high rates of withdrawal and poor performance. Diversity has also been differentiated between task-related and relations-oriented attributes. Task-oriented attributes are related to knowledge, skills, abilities needed in the workplace (e.g. function, tenure, education) and relations-oriented attributes include demographics such as age, sex, race and ethnicity that shape interpersonal relationships but do not have a direct bearing on performance (Jackson, et al., 2003).

Furthermore, task-related or functional diversity also has multiple conceptualizations including as dominant function diversity (the diversity of functional experts on a team), intrapersonal functional diversity (the aggregate functional breadth of team members), functional background diversity (the degree of difference in the complete functional backgrounds of team members) and functional assignment diversity (diversity in the functional assignments of team members). Different forms of functional diversity can have different implications for team processes and performance (Bunderson & Sutcliffe, 2002). How diversity is measured within groups and between groups varies based on the conceptualization and attributes selected.

Because functional diversity is associated with differences of opinion and perspective, it is possible that these differences may result in less effective performance (Bunderson & Sutcliffe, 2002). Cronin and Weingart (2007) labeled the source of this conflict as "representational gaps," which are differences in the way team members define or conceptualize team problems. Functionally, representational gap reflects differences between team members' problem definitions that will ultimately affect group problem solving. A representational gap is a group-level phenomenon that arises as a function of the cognition of individuals working together to solve a problem (Cronin & Weingart, 2007).

## 2.2 Trust and Organizational Resilience

Relational constructs of trust have been variously derived from the views of personality theorists rooted in individual personality differences and the specific developmental and social contextual factors that shape this, the views of sociologists and economists, who focus on trust as an institutional phenomenon based on the trust individuals put in those institutions and finally the views of social psychologists, who focus on interpersonal transactions between individuals that create or destroy trust at interpersonal or group levels (Worchel, 1979). The crux of this study is based on a social psychological definition of trust. In a professional relationship, Lewicki & Bunker (1996) theorized trust development as a three-stage model based on the assumption of two parties entering into a relationship with no prior history between them.

Calculus-based trust, or deterrence-based trust, is based on assuring consistency of behavior. The threat of punishment is likely to be a more significant motivator than the promise of a reward. Trust actions are rational and outcome maximizing. Knowledge-based trust, is grounded in the other's predictability and being able to anticipate behavior. This type of trust relies on information rather than deterrence and develops over time, largely as a function of parties having a history of interaction that allows for a generalized expectancy of behavioral predictability. Regular communication is key to this process. Identification-based trust, is based on identification with the other's desires and intentions. Trust exists because both parties develop a mutual understanding and can effectively act for each other. This permits a party to serve as the other's agent in transactions (Lewicki & Bunker, 1996).

In the context of natural resource management, effective collaborations between multiple stakeholders across social, political, jurisdictional and national boundaries and spectra highlight the fact that trust serves as a vital lubricant to the collaborative process, though trust development is fraught with challenges and inequitable power distributions (Stern & Coleman, 2015). The authors identify four types of trust:

(1) Dispositional – general, context independent predisposition in individual to trust/distrust.
(2) Rational – Based primarily on expectations of reciprocity or perceived utility in strategic interaction or on predictability and past performance with relation to costs and benefits of actions.
(3) Affinitive – Focus strongly on trustor's perceptions of the benevolence, integrity and other social characteristics of the trustee and through shared experiences, shared identities, connectedness etc.

(4) Procedural – Based on interactions between positive control systems and other forms of trust. Trust in procedures or systems that decrease vulnerability of the potential trustor.

Stern & Baird (2015) state that these different types of trust can fit different niches within an institution and serve different functions in NRM that can ultimately support or fail to support the institutional mission. Scale is an important factor that shapes the distribution and function of trust types and degrees in NRM institutions. NRM institutions typically involve multiple types of active and passive participants, including government agencies, NGOs, private industry and private citizens acting collectively and as individuals. Trust, for each of these entities, can exist at multiple scales (Stern & Baird, 2015).

Borrowing from ecological resilience and diversity conceptualizations, Stern and Baird (2015) present trust richness and trust evenness as components of trust diversity. Trust richness is defined as the number of different types of trust exhibited within a network; trust evenness is defined as the relative abundance of trust types within a network. This is applicable to positive trust, where distrust and lack of trust are treated separately. Their theoretical representation of trust diversity and its contributions to institutional resilience are illustrated in Figure 2.

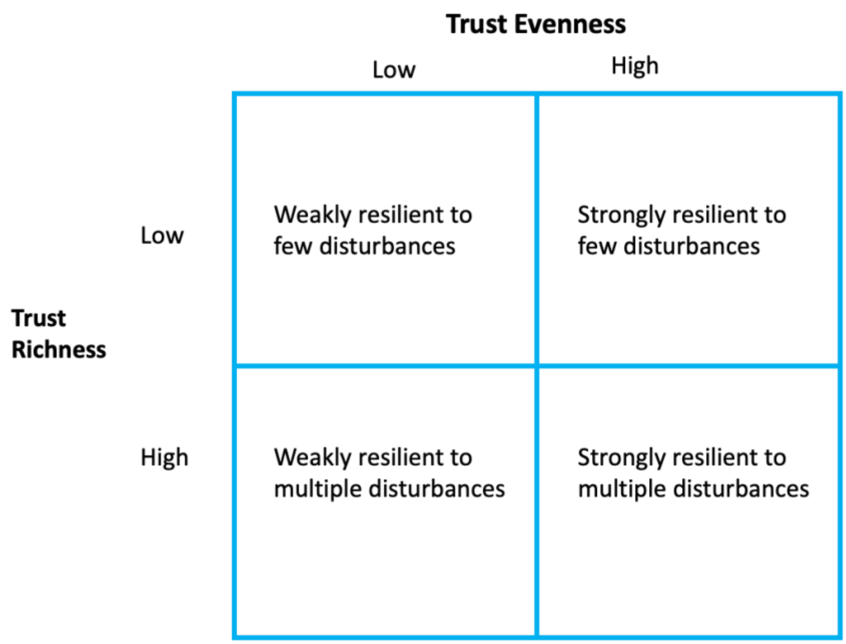


**Figure 1. 2:** Trust Ecology Framework and Relationship to Organizational Resilience (Stern & Baird, 2015).

When a disturbance affects one type of trust, other types of trust, or trust relationships, can help to buffer the negative effects of the disturbance. For example, affinitive trust may help buffer a performance failure from a trusted entity. Similarly, systems-based or procedural trust might help to buffer the effects of personnel turnover while interpersonal trust is slowly rebuilt. When trust richness and evenness are both high, an institution may be strongly resilient to multiple disturbances. In cases of low richness and high evenness, or high richness and low evenness, we may expect trade-offs between the magnitude and the range of disturbances to which the institution may be resilient. When richness is low and evenness is high, redundancy may exist, but only for a small number of functions. Alternatively, when richness is high and evenness is low, few redundancies exist (Stern & Baird, 2015). This study builds on this theoretical foundation to assess institutional resilience by measuring intra-institutional diversity and how the resulting trust ecology contributes (or not) to institutional resilience.

## 3. The Colorado Basin Case Studies: Overall Institutional Context

The seven basin states came together in 1922 in order to resolve the equitable division and apportionment of the use of the waters of the Colorado River system. The result of this was the apportionment of 7.5 million acre-feet per year equally to the Upper and Lower Basin states, respectively, for exclusive beneficial consumptive use, with Mexico getting the surplus over and above the aggregate of the quantities specified. The requirement of the Colorado River Compact was that Upper basin states not cause the river flow at Lee's Ferry to be depleted below 75 million acre-feet for any period of ten consecutive years nor withhold water to Lower basin states.

Later amendments to the agreement included the 1928 Boulder Canyon Project Act authorizing the construction of the Hoover Dam, the 1944 Mexican Water Treaty which allocated 1.5 million acre-feet to Mexico, and the 1948 Upper Basin Compact which solidified the water allocation amounts between the Upper Basin states. Additionally, the Colorado River Storage Project of 1956 authorized the construction of Glen Canyon, Flaming Gorge, Navajo and Curecanti dams for river regulation and power production as well as for irrigation and other uses. The Colorado River Basin Project Act of 1968 authorized the construction of a number of water development projects in both the upper and lower basins, including the Central Arizona Project (CAP). It also made CAP water supply subordinate to California in times of water shortage. Finally, Minute 242 of the US-Mexico International Boundary and Water Commission of 1973 required the United States to take actions to reduce the salinity of water being delivered to Mexico at Morelos Dam. This resulted in the Colorado River Basin Salinity Control Act of 1974 which authorized desalting and salinity control projects including the Yuma Desalting Plant, to improve Colorado River quality (USDOI, 2008).

The main problem arising out of these was that these amounts were overallocations based on measurements taken at Lee's Ferry during greater than average wet years. Among the Upper Basin states, Colorado has senior rights with 3.9 million acre-feet allocated, Utah – 1.7 million acre-feet, Wyoming – 1.0 million acre-feet and New Mexico – 0.85 million acre-feet. The Lower Basin states includes California as a senior rights state with 4.4 million acre-feet, followed by Arizona at 2.85 million acre-feet and finally, Nevada with 0.30 million acre-feet (WaterEncyclopedia, 2020). Another problem is that since implementation of the 1974 Salinity Control Act, measures have been put in place to reduce the annual salt load of the river by more than 1.3 million tons. The salinity concentrations at Hoover, Parker and Imperial dams has been reduced by more than 100 mg/l. However, even with these efforts, the quantified damages to U.S. users are still approximately $454 million per year, with projected damages to increase to $574 million per year by 2035 if the Program does not continue to be aggressively implemented (Keeler, 2017).

### 3.1 Institutional Context – Upper Colorado River Endangered Fish Recovery Program (UCREFRP)

This program was developed in 1988 as part of a cooperative effort that involved many of the agencies and organizations that have an interest in how the Upper Colorado River Basin and its resources are managed. These include the States of Colorado, Utah and Wyoming, the US Bureau of Reclamation, the US Fish and Wildlife Service (US FWS), water development interests and environmental organizations. The main impetus was to balance water development and also ensure compliance with the Endangered Species Act that came into effect in 1979. The goals of the program were to bring back four native fish species that were endangered due to intensive water development activities. These species include the humpback chub (*Gila cypha*), bonytail chub (*Gila elegans*), the Colorado pikeminnow (*Ptychocheilus Lucius*) and the razorback sucker (*Xyrauchen texanus*).

The States of Colorado, Utah and Wyoming determine how the river system's water resources are developed and to fulfill legal requirements that could constrain water resources development. The program is organized in a hierarchical structure with the Program Director overseeing the Implementation Committee whose primary responsibility is to interface with the US Congress and the Secretary of the Interior; the Management Committee which oversees program implementation and decision-making; the Biology Committee, the Water Acquisition Committee and the Information and Education Committee who oversee the science, business and communication aspects of the program respectively.

### 3.2 Institutional Context – Lower Colorado River Multi-Species Conservation Program (LCR-MSCP)

After critical habitat was listed for the razorback sucker and bonytail in 1994, representatives from agencies responsible for water and power management along the lower Colorado River met to discuss a comprehensive plan to conserve native species and their habitats in compliance with environmental compliance under the Endangered Species Act. In April 1997, the USFWS issued a Biological and Conference Opinion to Reclamation covering routine operations and maintenance activities along the Colorado River from Lake Mead to the Southern International Boundary (SIB). That biological opinion served two purposes: it provided Reclamation with Endangered Species Act compliance through 2002 (it was subsequently extended through 2005) and called for stakeholders along the lower Colorado River to develop and implement the Lower

Colorado River Multi-Species Conservation Program (LCR MSCP). On April 4, 2005 Department of the Interior Secretary Gail Norton and representatives from agencies within Arizona, California, and Nevada signed documents to implement the LCR MSCP.

The program area extends over 400 miles of the lower Colorado River from Lake Mead to the southernmost border with Mexico, and includes lakes Mead, Mohave, and Havasu, as well as the historic 100-year floodplain along the main stem of the lower Colorado River. The HCP calls for the creation of over 8,100 acres of habitat for fish and wildlife species and the production of over 1.2 million native fish to augment existing populations. The plan will benefit at least 27 species, most of which are state or federally listed endangered, threatened, or sensitive species. The Bureau of Reclamation is the implementing agency for the LCR MSCP. Partnership involvement occurs primarily through the LCR MSCP Steering Committee, currently representing 57 entities, including state and Federal agencies, water and power users, municipalities, Native American tribes, conservation organizations, and other interested parties, which provides input and oversight functions in support of LCR MSCP implementation. Program costs are evenly divided between the Federal government and non-federal partners.

## 4. Method

Diversity analysis in organizational and management literature has been heavily reliant on horizontal surveys and questionnaires that elicit people's attitudes and reactions to certain issues (Miller, Burke, & Glick, 1998; Kilduff, Angelmar, & Mehra, 2000; Simons, Pelled, & Smith, 1999; Ricardo, 2000). Some studies rely on focus group discussions and interviews with organizational personnel (McIntosh & Morse, 2015; Gilbert & Ivancevich, 2000; Mor Barak, Cherin, & Berkman, 1998).

Fiol (1994) used codes to measure consensus building around the content and framing of meanings to determine how diverse interpretations fostered innovation and collective learning. This study uses a similar method to analyze attitudinal diversity based on content analysis. For the purposes of analysis, the program websites were accessed for archival material, specifically for the meeting minutes for every year of the existence and functioning of both the UCREFR and LCR-MSC programs. The meeting minutes for the programs were coded using defined codes for assessing the diversity of attitudes present in each meeting, ranging from positive to negative, including neutral expressions. The UCREFRP has a much richer and more extensive dataset than the LCR-MSCP, which is quite sparse. The datasets used are available at https://osf.io/j36ry/.

Assessment of attitudinal diversity is seen as a variance of views/opinions/articulations around each meeting agenda and the goal and task interdependence for that period. The meeting agenda is taken as a baseline around which attitudinal variation is measured. Attitudes are divided into 4 categories for a more fine-grained analysis – Supportive, Clarifying, Conditional and Critical.

A "Supportive" code was assigned to text entries where all statements in a discussion on the agenda that are positive or supportive of the agenda based on linguistic qualifiers that include but are not limited to "should be supported/accepted", "should not be rejected", "suggested/asked that", "proposed that", "….if deemed necessary", "agreed that" and so on.

A "Clarifying" code was assigned to text entries where all statements in a discussion on the agenda are seeking further information or clarification on the topic and/or questioning issues further but have not yet expressed a marked positive reaction.

Linguistic qualifiers include but are not limited to “asked if/why…”, “expected that…”, “responded that….”, “noted/stated that….”, “clarified that” and so on. This code is viewed as neutral because it illustrates the general question-answer and clarification that is sought in any discussion of the agenda topics.

A “Conditional” code was assigned to text entries where all statements in a discussion on the agenda that emphasize the fulfilment of certain conditions before the theme of the agenda is accepted. Since the tone of the code is more of a conditional acceptance with negative connotations, it is taken as a negative-leaning attribute. Linguistic qualifiers include but are not limited to “before a decision is made…”, “what is gained/intended by…?”, “if…can be changed/modified/developed/excluded…”, “support, but….”, and so on.

A “Critical” code was assigned to text entries where all statements in a discussion on the agenda that are critical to/of the agenda. This code is the most negative-leaning in tone. Linguistic qualifiers include but are not limited to “not yet convinced….”, “…could make things more difficult/challenging”, “concerned about/expressed concern about…”, “reconsider, pending…”, and so on.

Intercoder reliability rating was conducted on 30% of the documents that were analyzed using the guidelines for computing inter-reliability rating (Hallgren, 2012). A total of 35 segments, taken from random document sections, were analyzed by the second coder independently. The total code numbers for each attribute for each segment were entered into a spreadsheet and intraclass correlation (ICC) calculated for the four main attitudinal diversity attributes before the codes were reconciled through discussion. ICC was chosen because the purpose was to assess the consistency and reproducibility of the measurements made by independent coders as some codes were clear-cut and some more ambiguous and contextual. The ICC was run on SPSS using a two-way mixed effects model with an absolute agreement definition. Table 1 below lists the descriptive statistics for ICC for each of the four main attitudinal variable categories.

**Table 1. 1:** Descriptive Statistics for Attitudinal Variable Sample.

| | Supportive | Clarifying | Conditional | Critical |
|---|---|---|---|---|
| Cronbach's Alpha | 0.914 | 0.828 | 0.756 | 0.744 |
| Std Dev Coder A | 3.02 | 3.56 | 1.28 | 1.24 |
| Std Dev Coder B | 2.85 | 3.41 | 1.31 | 2.34 |
| Variance | 0.015 | 0.069 | 0 | 0.216 |
| Inter-Item Correlation | 0.843 | 0.707 | 0.608 | 0.714 |
| ICC Average Measures | 0.915 | 0.830 | 0.761 | 0.721 |
| 95% CI Lower Bound Average Measures | 0.833 | 0.664 | 0.524 | 0.446 |
| 95% CI Upper Bound Average Measures | 0.957 | 0.914 | 0.880 | 0.860 |

Finally, a sample of codes are displayed for each category of codes to show the best examples of coding that fall under that category, in the table in Appendix A. In other words, a small sample of those codes that clearly fall into one category based on the operational definitions of that category are listed to provide a clearer depiction of how the codes were used. Definite examples of statements are those that clearly depict linguistic qualifiers for a particular category. Ambiguous examples are coded based on the context of the discussion about the agenda. The latter category is why, for example, a linguistic qualifier such as “countered” would be taken as supportive because the countering is in support of the agenda rather than critical of it or a linguistic qualifier like “said that” would fall into a condition category rather than a clarifying one because it is conditional on a particular action.

## 5. Results

Figures 3 and 4 show the temporal patterns of distribution of attitudinal diversity for the UCREFRP and LCR-MSCP, respectively. Both programs have their inception in a desire to avoid jeopardy or financial penalties associated with the impacts of continued water development activities on critically endangered fish species as well as on incidental take from recreational fishing activities. Attitudinal diversity variation tends to lessen over time in the UCREFRP case. We observe that critical and conditional attitudes were more prevalent over the first 10-year period starting from 1988 and lessened after that. Overall, there is growing convergence toward agreement based on the higher supportive and clarifying attitudes around the agenda issues and a diminution of critical attitudes over time.

The 1994-1997 period was not showing success in terms of native fish protection and there was concern about further investment until the situation showed improvement. This is indicative of rational trust at play as possible performance failures of measures implemented to manage invasive fish populations was the major disturbance in this period. However, with the implementation of hatchery programs for native fish breeding and fish passage constructions, affinitive trust was again re-established as native fish populations again showed recovery potential. The prevalence of discussions surrounding continued authorizing legislation also illustrates that at significant points in the program's lifetime, there was also the prevalence of system-based or procedural trust, as program co-operative agreement was extended more than twice in the history of the program – in 2001 and 2009 – to continue through 2023 and beyond.

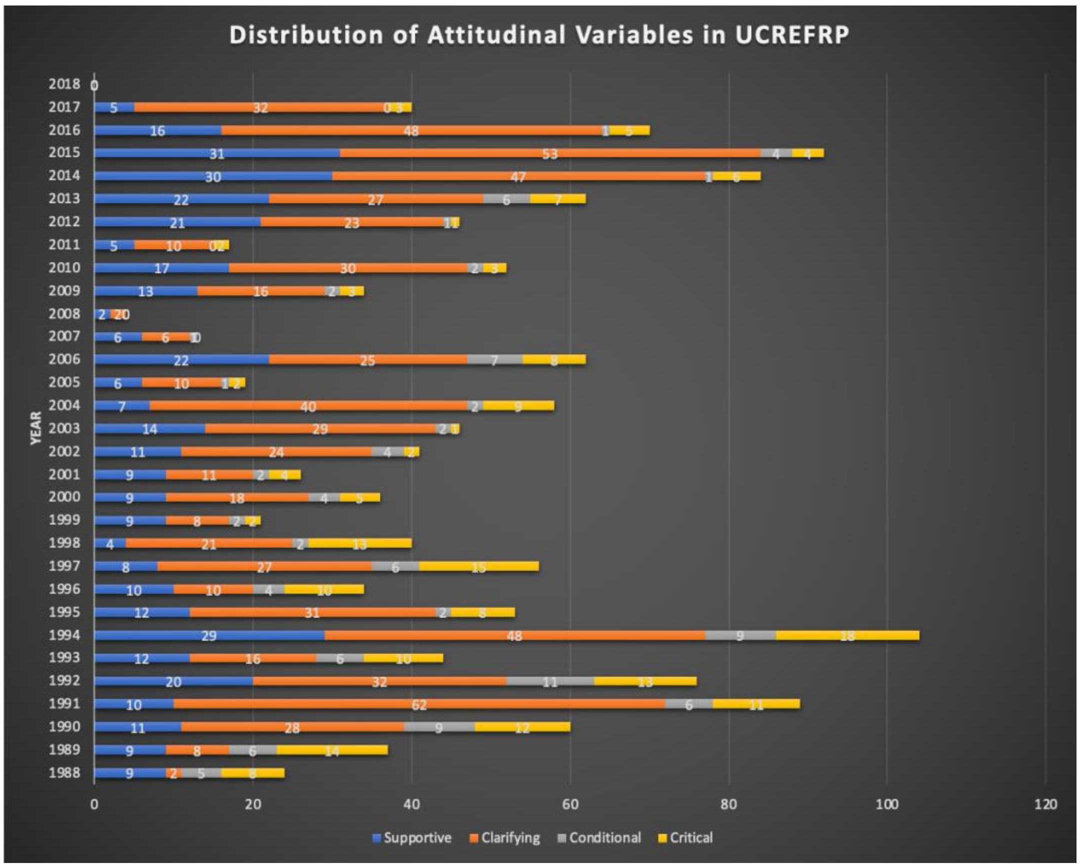


**Figure 1. 3:** Trends in Attitudinal Diversity for UCR-EFRP.

It is evident that the period from the inception of the UCREFRP to 2000 showed a greater attitudinal diversity than the period post-2000 to present. The years 2008 and 2018 show absence of good data for analysis and are discounted. The period 1988-1998 was the period when the most important issues such as institutional membership, native fish recovery, non-native fish management and capital investment projects were closely discussed with variable success over the period. The 1994-1997 period depicts a period of setbacks in program goal achievements and resulted in increased efforts to incorporate science-based approaches to flow management to increase propagation and survival of listed native fish species. The period from 1988-2000 therefore signifies a phase when consensus was less easily achieved due to implementation challenges. However, post-2000 there appears to be greater positive responses with the agreement being higher. The LCR-MSCP does not have sufficient and consistent data over time. But what can be observed from Figure 4 is that critical attitudes have persisted or occurred at discrete intervals over time. This is supported by evidence that details that a building dissension around key program goals resulting in legal settlement of a water right dispute centered around acquiring water leases for fish conservation (Arizona Department of Water Resources vs. Mohave County, 2015). During the period 2009-2010, the acquisition of land for habitat construction was being considered, toward housing listed endangered species including the Southwestern Willow Flycatcher. One of the potential land acquisitions considered was Planet Ranch, which is located approximately 20 miles east of Parker, Arizona upstream of the Bill Williams River National Wildlife Refuge. It was a site owned by Freeport McMoran Mineral Corporation. The land is 3418 acres with 5549 acre-feet of water rights attached to it. Initial discussions merely kept the proposal under consideration. This period indicates that rational trust was strong and prevalent during this period of program activity collaboration and expansion.

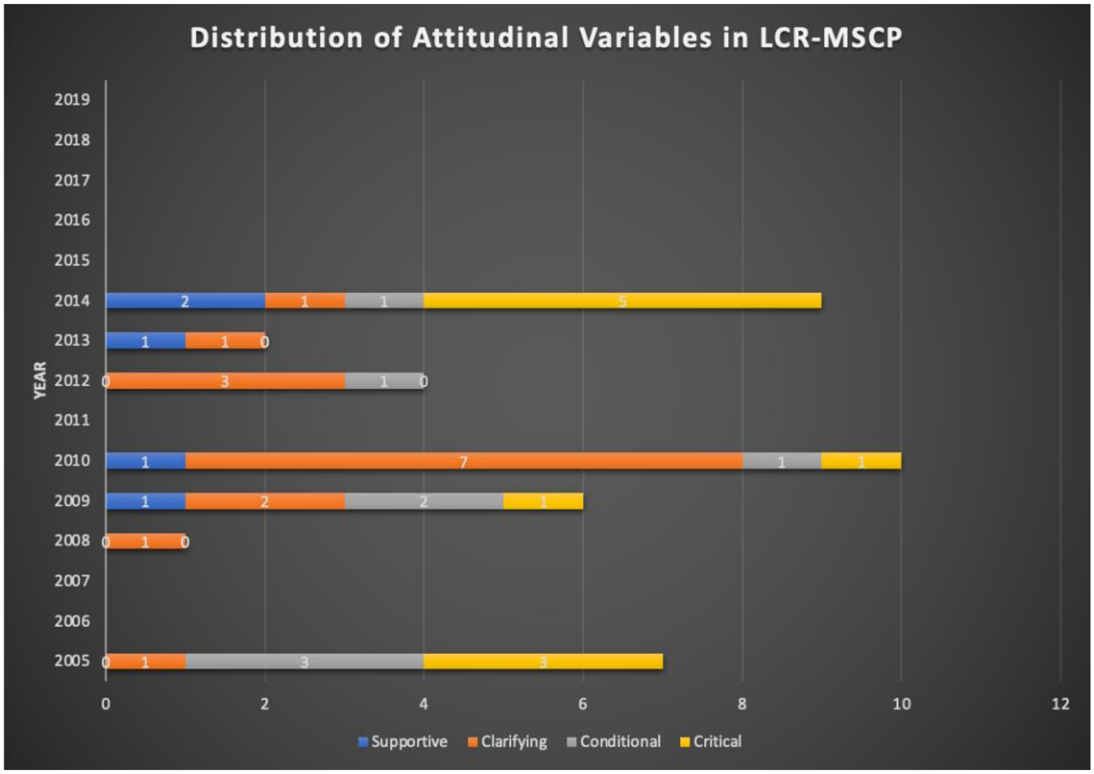


**Figure 1. 4:** Trends in Attitudinal Diversity for LCR-MSCP.

When the acquisition became more viable, Mohave County Water Authority and the City of Bullhead registered opposition to the acquisition on grounds that there was lack of involvement of the local government in the final agreement, particularly in relation to settlement provisions and water rights transfers. The LCR-MSCP has arbitration measures where the Steering Committee calls for a deciding majority vote on an issue if agreement cannot be reached through discussion. This vote found overwhelmingly in favor of acquisition of Planet Ranch for the program. However, the matter was further taken to the courts with the final decision being made in favor of the Program. In December 2015, LCR-MSCP acquired a lease for Planet Ranch to be used as a conservation area. There was a gradual build-up of concern and then opposition until the 2013-2014 period when the acquisition was brought to the table for implementation. This episode and the continuance of the program through the conflict shows the operation of procedural trust in arbitrating conflict and then reverting to rational trust for continued operation.

Table 3 below illustrates the various environmental disturbances that have affected the two organizations over time, how the organizations responded, and how attitudinal diversity shaped the typed of trust that the responses depicted. Environmental disturbances are characterized as either press or pulse events and are either institutional or biophysical in nature. Press disturbances are long-term disturbances with long-term impacts, while pulse disturbances are temporary in nature and while they may cause substantial impacts, there is potential for the system to rebound or recover. Institutional disturbances can take the form of broad socio-cultural norms and values, legislation and regulatory policies and market factors, while biophysical disturbances include drought (both episodic and chronic), climate change and the presence of invasive species.

**Table 1. 2:** Characterization of Organizational Responses, Attitudinal Diversity and Trust Types to Environmental Disturbances.

| Environmental Disturbance | Type | Region | Year | Organizational Response | Attitudinal Diversity | Trust Ecology |
|---|---|---|---|---|---|---|
| Enforcement of Endangered Species Act, 1978 | Institutional Press | Upper Basin | 1987-present | UCREFRP formation with greater vertical nested polycentricity to mitigate financial or legal penalties for non-compliance with USFWS as greater authority | Resting on inclusion-exclusion aspects of program participants and pathways to achieving program goals. | Presence of combination of dispositional trust based on advancing self-interest and rational trust based on utility of interactions and cost-benefit calculations. |
| | | Lower Basin | 2005-present | LCR-MSCP formation with greater horizontal polycentricity to mitigate financial and/or legal penalties for non-compliance with Reclamation and USFWS as co-leads but Reclamation having greater authority | Resting on designation of authority in the decision-making Steering Committee and inclusion of program participants | Presence of both dispositional trust and rational trust |
| Weakening of ESA regulations | Institutional Pulse | Upper Basin | 2017-2020 | Based on 5-year Species Status Assessments (SSA), the program (with approval from US Fish & Wildlife Service) proposed downlisting of humpback chub and razorback sucker species from endangered to threatened in 2018 | Agreement on further extension of Program post 2023 because of continued need for aggressive non-native fish control which has not been successful. | Generation and maintenance of affinitive trust in addition to continuation of rational trust. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Lower Basin | 2017-2020 | ---- | ---- | ---- |
| Exceptional low flow years | Biophysical pulse | Upper Basin | 2002, 2012, 2018 | Implementing long-term co-ordinated reservoir reoperations with either one or two spike flows depending on severity of hydrologic drought. 2018 saw an unpredecented amount of collaboration and cooperation in releasing needed water to maintain minimum flows to avoid dangerously dry conditions in key stretches. | Wide-spread agreement and discussion about the details of proposed plans and implementation pathways. | Generation and maintenance of affinitive trust and procedural trust. |
| | | Lower Basin | 2012, 2018 | ---- | ---- | ---- |
| Climate change, megadrought, invasive species | Biophysical press | Upper Basin | 2000 – present | Recognition that flow releases might be subjected to hydrologic limitations and not endangered fish releases and continued prioritization of invasive species control efforts through information & awareness campaigns to garner widespread public support | Agreement and discussion around continued actions and support for program continuation | Presence of procedural trust and continuation of rational and affinitive trust. |
| | | Lower Basin | 2005 – present | Strategies to increase coverage for flow reductions due to appropriation below Hoover, and Davis dams and between Parker and Imperial dams with focus on increasing storage in Lake Mead | Resting on acquisition of water leases for conservation areas that threatened municipal water rights and was resolved via legal action | Presence of rational and procedural trust. |

## 6. Discussion

This section is organized into two parts. The first part describes the environmental disturbance – organizational response dynamic and what role attitudinal diversity plays in mediating the relationship between responses and the specific types of trust at play. The second part delineates the linkages between the trust types based on responses recorded and what their distribution implies for organizational resilience to various disturbances. The third part finally utilizes the trust ecology to characterize organizational resilience to disturbances and discusses the implications with respect to broader biogeographic and socio-political contexts.

### 6.1 Environmental Disturbance – Organizational Response Dynamic

Organizational responses to institutional press disturbances reveal that the enactment of the Endangered Species Act (ESA)was a major impetus that led to the formation of both programs as the driving impetus for stakeholders including water uses and energy and water development companies was to avoid the financial and legal penalties accruing from non-compliance. The attitudinal trust based on initial document review reveals that rational cost calculations formed the basis of inclusion of parties to the programs. Also, because the programs were reconstitutions of existing water governance systems with a broadening to include conservation governance organizations at federal, state, local and non-state levels, a large portion of dispositional trust was also at play because the stakeholders were familiar with each other with set expectations of roles to be fulfilled.

Because of historic episodes of hydrologic drought, the responses to biophysical pulse events at specific years reveal that, at least, in the case of the UCREFRP, contingency planning led to a maintenance of conservation priorities with greater agreement being engendered. The nature of this agreement was predicated on affinitive trust, as by this time, more than a decade into the program, the parties had extensive familiarity with the priorities of participating organizations regardless of representative turnover. With respective obligations already clear-cut, and significant policy, legislative, financial and technical investments underlying the program, there was the presence of both affinitive and procedural trust. The LCR-MSCP had no significant responses recorded for biophysical pulse events.

Institutional pulse events such as the weakening of the ESA, elicit a response from the UCREFRP based on a 5-year status assessment, which points to a business-as-usual approach to a pre-set plan. Because of substantial tangible and intangible investments, the biophysical press events, as well, have resulted in greater agreement being fostered on program actions in fulfilment of the initial program objectives and this points to the addition of procedural trust as well to the other three types of trust at play. The LCR-MSCP did not have significant responses recorded for institutional pulse events but because the program was intended, since inception in 2005, for a period of 50 years, the underpinning of rational trust has not changed, though an instance of procedural trust was brought into play in a water rights dispute where development and conservation interests were not aligned.

The response to institutional press disturbance was morphogenetic or transformational through a process of colonization for both cases. It can be seen, furthermore, that after the initial morphogenetic response, the subsequent responses to other listed disturbances were more of a morphostatic or transitional nature, with some reorientation of tangible organizational sub-systems and interpretive schemes.

## 6.2 Trust Ecology – Organizational Resilience Dynamic

The role of attitudinal trust lies in mediating the relationship between organizational responses to environmental disturbances and the types of trust that are in play in these interactions. People's decisions to engage in trusting behavior occurs by paying attention to what information they attend to, and also, how they interpret and construe that information (Kramer, 2010). Organizational rules (rule-based trust) contribute in many ways to members' positive expectations about others' behavior (March, 1994). Role-based trust is based on fiduciary responsibilities and obligations associated with the roles a member occupies (Kramer, 2010). Based on the attitudinal diversity recorded for the institutional press disturbances in both recovery programs, it appears that both these factors contribute to the formation of dispositional trust, in addition to rational trust based on cost-benefit considerations to non-compliance with the ESA. The foundational documents for the programs clarify the roles and responsibilities of each party and any attitudinal diversity rested around these issues. In the case of the UCREFRP, The later addition of other types of trust increased the number of different types of trust at play over the time-span of the program and therefore increased trust richness over the same period. The relative abundance of the different trust types was low during the formative years of the program with less number of trust types present initially, but the addition of other trust types grew after the first decade and the relative abundance of these trust types depicts greater trust evenness growing over time. The program demonstrates a movement toward high trust richness and high trust evenness over time.

The LCR-MSCP was founded on a similar pattern of trust types as the UCREFRP. However, organizational responses to latter press and pulse events do not show the additional of more types of trust evenness because the relative abundance of trust types is restricted to two out of four trust types over time as evidenced by the response to biophysical press events. The reliance on procedural trust to settle a legal dispute overshadows the dispositional trust that led to the formation of the program. Therefore, with a low number of trust types present and a low relative abundance over the 15-year span of the program, both trust richness and trust evenness are low for the LCR-MSCP.

## 7. Conclusion

The results from coding and statistical analysis indicate that Proposition 1 is supported in the UCREFRP case but the LCR-MSCP does not have enough data for analysis. Among the attitudinal variables, there is a clear downward trend in the negatively associated attitudes, with a very high variance in the positively associated attitudes in the UCREFRP. With regard to longevity and resilience of the institutions, Proposition 2 is supported by the results. There is lesser trust richness in the initial years of the project and this is true both of the more mature UCREFRP and the more recent LCR-MSCP. Both programs exist in the space between balancing water development interests with species and habitat protection. Therefore, the presence of rational and procedural trust underpins both institutions especially in the "Development" phase and is the primary cause of their initial resilience, albeit weak. The results indicate that trust richness and evenness increases over time in the UCREFRP. Over time, the UCREFRP has shown increasing trust richness and evenness has led to stronger resilience evolving in the institution making it resilient to multiple disturbances. This is not yet evident in the LCR-MSCP and considering the different dynamics and water allocation priorities of the Lower Basin states, it is not clear whether dispositional and affinitive trust is likely to feature large in the future.

The pre-formation years of both UCREFRP and LCR-MSCP was a period of extensive discussion and negotiation around the importance of coming to terms with avoiding the penalties of non-compliance on endangered fish species conservation when water development or recreational fishing is undertaken. The formation of the programs entailed substantial reconstitution of existing authority structures of river basin management at multiple levels that traditionally relied on a river management authority – the Bureau of Reclamation delivering water entitlements to State and local water users as well as operating hydroelectric dams with power users. The new structure after a broadening in authority to include the U.S. Fish & Wildlife Service (USFWS), state wildlife agencies and non-state environmental groups showed differential power dynamics that has resulted in differential program policies and strategies. The Upper Basin had the USFWS as the dominant authority in the UCREFRP, while the Lower Basin had Reclamation as the dominant authority in the LCR-MSCP. Consequently, the organizational change that occurred through a process of evolution from traditional structures to reconstituted recovery organizations was of a morphogenetic nature (Laughlin, 1991).

Biophysical and geographic realities have also played a significant role in program constitution and continuation. The UCREFRP is played out over a substantial portion of the Upper Basin including not just the large rivers below dams and reservoirs, but also tributaries and small creeks because one of the main goals of the program is to provide connectivity to migrating endangered fish so they could reach their traditional spawning grounds, for which there was substantial financial and physical investment commitment. These same commitments were also extended to large-scale coordinated reservoir reoperations, flow experiments to ensure recovery of endangered species and disrupt invasive species propagation as well as other strategies for rampant invasive species control. The scale and number of program goals and activities combined with the high level of tangible and intangible investment in the program over a period of over three decades indicates that though the program started out based on rational trust with some level of dispositional distrust in questions of initial program membership, these evolved to incorporate affinitive and procedural trust as the program matured in subsequent decades. Therefore, with a high level of trust richness and trust evenness over time, the UCREFRP is strongly resilient to multiple disturbances.

The LCRMSCP coverage is mostly along the main stem of the Lower Colorado Basin and because of the presence of numerous large dams embedding infrastructural dependencies and the more acquisitive and aggressive water rights politics of the Lower Basin states (Huckleberry & Potts, 2019), maintaining connectivity is impossible. The goal here is to maintain discrete backwater and conservation habitat for preservation of endangered species, garner water through leases or reservoir supply and increase coverage of both aquatic and terrestrial endangered species to minimize risk. Therefore, the dominant presence is that of rational trust based on substantial cost-benefit calculations and procedural trust based on systems to resolve water rights conflicts. With low levels of both trust richness and trust evenness over time, the LCRMSCP is weakly resilient to a few disturbances.

As river restoration in arid regions takes on new and more urgent meaning, it is imperative that institutions formed to facilitate this goal are constituted in a long-term sustainable manner and are resilient to internal and external disturbances. This study used an in-depth content analysis method to tie the presence of certain intra-institutional diversity attributes to group cohesiveness, trust and ultimately to institutional resilience. The typologies that can be used to arrive at a diagnosis of institutional resilience as well as point to vulnerabilities that can be addressed, are many and utilizing novel methods of analysis to inform strategies that enable long-term sustainability of key institutions for guarding vital ecosystem services is immensely beneficial in the NRM institutional space.

PART II: ASSESSING ECOLOGICAL RESILIENCE AND THE EFFECTIVENESS OF ADAPTIVE MANAGEMENT: A CASE STUDY OF THE UCR EFRP

## 1. Introduction

River and riparian ecosystems continue to be threatened by a diverse array of environmental and anthropogenically-induced shocks. In the face of these shocks, ensuring the long-term survival of a river system can be accomplished by addressing and improving its resilience. Resilience as used in the context of ecological and natural resource management has its roots in Holling's (1973) definition of resilience as the quantity of disturbance a system can tolerate before it changes into an alternative regime. Particularly relevant is the Boltz et al. (2019) characterization of three capabilities of a resilient freshwater system - **persistence**, which refers to a natural system's ability to maintain coherent function under changing conditions and disruption without significant identity alteration; **adaptability**, which refers to a system's ability to maintain coherent function by modifying its identity to accommodate change; **transformability**, which refers to a system's ability to change its identity and to establish a new function in a novel equilibrium when pushed beyond the threshold of its present state (Boltz, et al., 2019).

Significant resources and investment have been directed to ensuring the "persistence" characteristic of resilience in river systems, particularly with respect to entrenched water allocations and grey infrastructure (Hatcher & Jones, 2013). Transformation is often seen by some as a consequence of system failure and collapse, and by others as an essential capability of a long-lasting system (Feola, 2014). However, it is increasingly been seen as a distinguishing factor between winners and losers (Boltz, et al., 2019). The subsequent section discusses the framework and implementation of adaptive management in natural resources with an emphasis on freshwater systems in the United States.

## 1.1 Adaptive Management of Natural Resources

Adaptive management of natural resources is expressly intended to decrease ecological uncertainty, for example about how a particular species within an area of interest may respond to changing climate or how the harvest method of a species affects its population structure and density. Where sufficient knowledge of resource dynamics and the influence of management on those dynamics are readily available, it is rather specific political, social or institutional challenges which represent the most considerable obstacles to progress and adaptive management may not be the appropriate approach to use (Rist, et al., 2013). Characterization of uncertainties as depicted in Figure 1, is also subjectively defined as aspects of any system and are open to re-interpretation and re-categorization. For instance, in fisheries management, stock assessments are characterized by high levels of uncertainty, and this total uncertainty can further be deconstructed into those surrounding natural mortality rate, fish migration patterns, and variability in fish's vulnerability to fishing gear (Rist, et al., 2013), climate change and other stressors. In freshwater ecosystems, uncertainties around stock assessments are most significantly tied to conservation of endangered fish and fish communities (Maitland, 1995).

Additionally, planners who confront management obligations that target complex and layered ecological phenomena must navigate multiple statutory authorities and regulations, and grapple with trade-offs among conservation objectives and integrate diverse stakeholder involvement (Greig, et al., 2013). Where species listed under the federal Endangered Species Act enter the equation, the complications that attend management often are multiplied (McFadden, et al., 2011). In such circumstances, uncertainties regarding the needs of target species can overwhelm the management agenda, and adaptive management may be selected by default as the primary means of bringing knowledge to conservation planning (Murphy & Weiland, 2014).

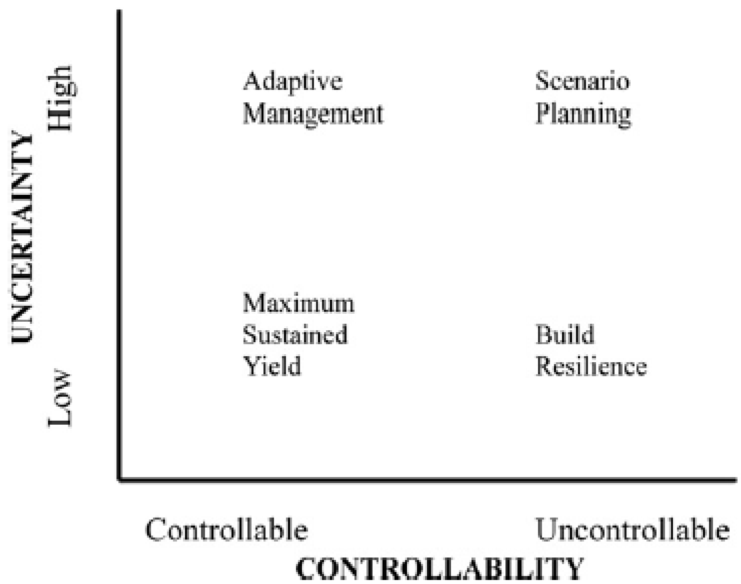


**Figure 2.1:** Types of Approaches Based on Levels of Controllability and Uncertainty *(Allen & Gunderson, 2011)*.

The United States Department of the Interior uses an adaptive management framework in a six-step process as a structure for conservation planning initiatives. Since its initial introduction and description, adaptive management has been hailed as a solution to endless trial and error approaches to complex natural resource management challenges. However, its implementation has failed more often than not, as it is effective in the implementation of only a small subset of natural resource management problems (Allen & Gunderson, 2011).

### 1.2 Design Flows and Biodiversity

The science of river restoration describes a variety of modifications of river channels and adjacent riparian zones and floodplains, and of the water, sediment and solute inputs to rivers (Bennett, et al., 2011) with the goal of improving hydrologic, geomorphic and/or ecological processes within a degraded watershed (Wohl, et al., 2015) and replacing lost, damaged or compromised elements of the natural system (Wohl, 2011). However, what constitutes improved river conditions is highly subjective and is a function of the dynamics of water demand and the various use values that the river is subject to. Distinctions have been made between restoration, which is primarily intended to reconnect rivers through infrastructure improvements, and projects designed to primarily reconfigure rivers through changing physical stream structures (Bernhardt & Palmer, 2011). Restoration improvements may also focus on creating conditions that are not particularly natural or historic, geomorphically or ecologically appropriate (Wohl, et al., 2015).

In the natural flow paradigm, the baseline flow regime provides the starting point against which the ecological effects of removing or changing particular flow elements can be predicted or hypothesized. The paradigm focuses on maintenance of biodiversity and basic ecological processes that underpin natural delivery of ecosystem services and is most applicable to rivers of high conservation value. This approach, however, is not appropriate for heavily regulated river systems, and the assessment of e-flows has focused on maintenance of these altered but valued river ecosystems (Acreman, et al., 2014). Dams can heavily modify the volume of water flowing downstream and change the natural flow regimes of the river. Maintenance of designer flows through dam re-operation is promising but constrained by existing water allocation entitlements, biological and physical conditions, socioeconomic limitations, political or legal impediments and physical features of existing dams (Richter & Thomas, 2007).

Environmental flows (e-flows) are increasingly used to help minimize the detrimental effects of dam management on river biota and are being widely recognized as critical to the restoration and conservation of freshwater ecosystems and species globally (Poff, et al., 2017); (Yarnell, et al., 2020). Designer environmental flows range from single events designed to achieve a specific goal, such as a flood for mobilizing sediment, to entire flow regimes designed to accommodate multiple ecosystem needs (Acreman, et al., 2014) across the aquatic food-web (Kennedy, et al., 2016) and can also vary from utilizing the natural flow regime paradigm (Richter, et al., 1996); (Poff , et al., 2010) to designing hydrographs through ecologically informed dam operations (Sabo, et al., 2017). Five critical components of the flow regime regulate ecological processes in river ecosystems: the magnitude, frequency, duration, timing and rate of change of hydrologic conditions. These in turn affect the water quality, energy budget, physical habitat and biotic interactions, all of which comprise the ecological integrity of the river system (Poff, et al., 1997).

Freshwater fish populations have undergone catastrophic decline, with nearly a third at risk of extinction, and populations of migratory fish falling by three-quarters in the last 50 years, with significant implications for food security, recreational use and conservation (WWF, 2021). Conservation of biodiversity in freshwater systems has taken on a new urgency in recent decades and the challenges are more pressing in arid and semi-arid regions where demand for water has tended to exceed available supply.

Biodiversity can be decomposed into alpha diversity (the number of species in a given location), gamma diversity (the number of species within a defined region) and beta diversity (the extent of change in community composition across sampling units) (Ruhi, et al., 2017). Partitioning of fish metacommunity diversity (into turnover and nestedness components) across locations has been studied in various streams (Kanno, et al., 2012); (Zbinden & Matthews, 2017); (Ragosch & Olden, 2019); (Faustino de Queiroz & de

Freitas Terra, 2019) with consistent evidence for community similarity within mainstem sites and with varying impacts of dispersal across space. Species turnover occurs in a habitat network when species are lost and replaced in habitat patches with different environmental conditions, and nestedness occurs when species are lost and not replaced (Baselga, 2010). This differential pattern of replacement across patterns leads to increased community dissimilarity or beta diversity. Dispersion can be a driver in metacommunity dynamics, either by homogenizing communities with high rates or by limiting them through dispersal limitations (Sarremejane, et al., 2017). Dispersal is greater through mainstems than in headwaters (Fagan, 2002) with compositional turnover typically being higher in headwater than in mid-order streams because of higher environmental variability (Finn, et al., 2011).

Studies of temporal metacommunity dynamics show high variability when partitioning is implemented for invertebrate metacommunities (Ruhi, et al., 2017). High temporal variability of stream invertebrate community structure was found to be directly related to the frequency and duration of drying events with fragmentation having a strong effect on recolonization processes (Crabot, et al., 2020). However, local and regional diversity patterns differed between invertebrate and fish communities, with both communities differing different recovery stages that were explained by different effects of physical and environmental distances at intermittent and perennial sites (Datry, et al., 2016) for wet neotropical streams. Fish metacommunities in desert rivers were strongly influenced by discharge anomalies and displayed persistence despite the presence of invasive species, with nestedness increasing after anomalous droughts (Ruhi, et al., 2014). A key finding of this study suggests that abiotic interactions more strongly affect metacommunity dynamics than biotic interactions in highly variable environments and that native assemblage was negatively impacted by droughts but favored by floods.

## 2. Upper Colorado River Endangered Fish Recovery Program (UCR EFRP)

The UCREFRP is a partnership of federal, state, local and non-state actors including water and power interests and environmental groups with the singular mandate of working to save endangered fish species in the Upper Colorado River Basin in accordance with federal, state and compact laws. It was initiated in 1988 with the signing of a cooperative agreement between Colorado, Utah and Wyoming, the Secretary of the Interior and Western Area Power Administration.

This study will explore the ecological effectiveness of restoration in the UCREFRP and also the effectiveness of the implementation of adaptive management approaches. The measure of restoration effectiveness speaks to immediate feedback loops between management actions taken and ecological responses recorded, while an assessment of adaptive management in this context will look at whether the iterative cycle of action-response is appropriate and effective in this situation. The main research question centers around the following questions:

***(1) What are the determinants of recovery program success?***

***(2) Is ecological resilience achieved through the program?***

***(3) Has adaptive management been effective in the face of environmental and anthropogenic shocks and stresses?***

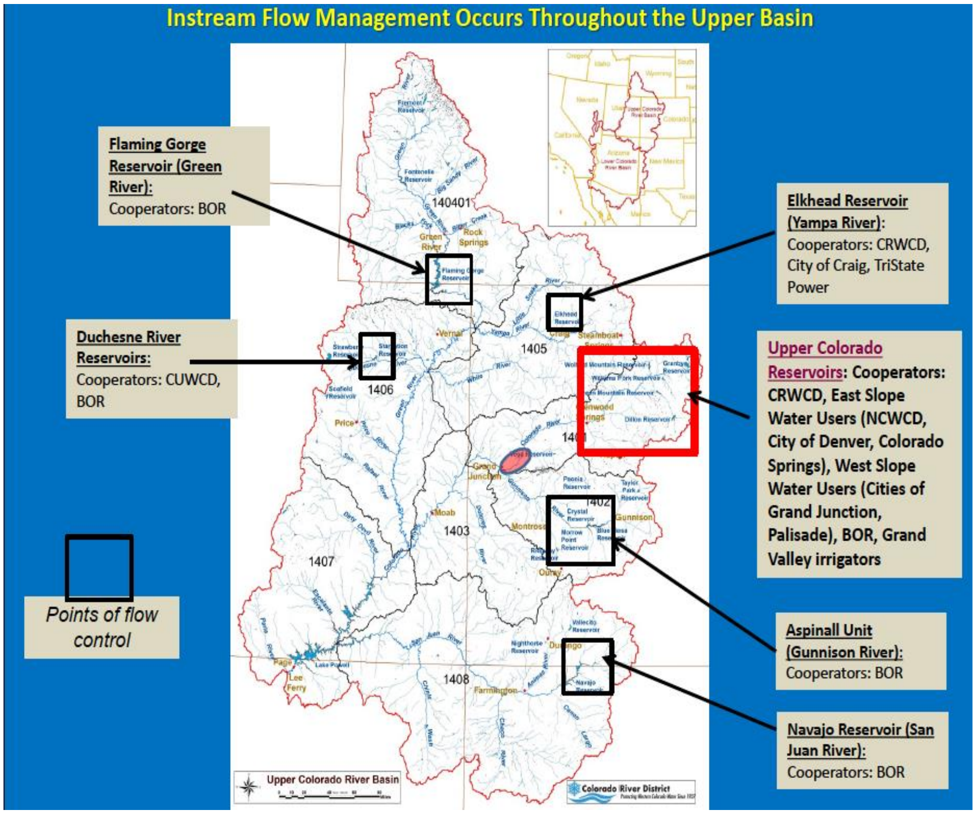


**Figure 2. 2:** Map of Upper Colorado Basin Areas Covered by UCREFRP and Points of Fow Control *(UCREFRP, 1992)*.

The novelty of this study lies primarily in the fact that it furthers extensive studies done on metacommunity dynamics by utilizing a temporal beta diversity approach and for the first time utilizing biotic predictors such as altered flow regimes **as well as** anthropogenic predictors in the form of hydrological, technological and ecologically based interventions to support endangered fish persistence and sustainability in the Upper Colorado Basin reaches. Secondly, it deconstructs the utilization of the adaptive management approach and analyzes its effectiveness and legitimacy in the face of environmental stressors. The implications of both studies are then discussed.

## 3. Methods

The dataset used was extracted from the Species Tagging, Research and Monitoring Systems (STREAMS) database that was developed and is currently managed by the Colorado Natural Heritage Program. The site provides fish data from the Upper Colorado and San Juan River Endangered Fish Recovery Programs that are aimed at recovery of endangered fishes in their respective river basins while allowing water development in those areas to continue. As a result of recovery efforts over the past two decades, primarily stocking and monitoring, a large quantity of data pertaining to both stocked and wild endangered fishes has been collected. A limited dataset containing only captured fish listings with abundance data, streams captured, year, sampling days and species information from all surveyed locations was extracted. From this dataset, a number of data relationships were organized.

### 3.1 Streamflow Computations

Streamflow data were extracted from the USGS Waterdata website using the *dataRetrieval* R package (DeCicco & Hirsch, 2021) for all sites listed on the STREAMS fish dataset. The locations comprised larger and mid-range streams, intermittent streams and creeks as well as constructed habitat, wetlands and reservoirs. Because the coordinates of the fish sampling locations were not available in the STREAMS dataset and only the generic stream name where sampling occurred, the UCR EFRP program documents were analyzed for location identifiers and the nearest USGS gauge data were identified and the streamflow values extracted.

Accurately quantifying regime variation, especially in highly variable ecosystems such as desert rivers requires focusing on residual variation, where catastrophes are defined as more extreme forms of stochastic variation (Sabo & Post, 2008). To quantify the effects of stochastic variation in streamflow, a Discrete Fourier Fast Transform (DFFT) analysis was run (Sabo & Post, 2008), using the *discharge* package in R (Shah, et al., 2019) for all shortlisted locations which primarily comprised larger river locations as well as smaller creeks and intermittent streams. Annual flow regime parameters calculated include annual flow variability Net Annual Anomaly (NAA), lowest and highest flow Spectral Anomaly Magnitude (LSAM and HSAM, respectively) and flood pulse extent ($FP_{ext}$).

For the purposes of this study, NAA values were used as one of the predictor variables in the final regression model. The flow regime and fish beta diversity datasets were then matched and a final selection of six sites were made for which there was consistent and significant data between the years 1987-2019. The shortlisted sites and their characteristics are shown in Table 1 below.

**Table 2. 1:** List of Selected Sites From Where Discharge Data Was Used.

| USGS Gauge | Station | Location | Latitude | Longitude |
|---|---|---|---|---|
| **09163500** | Colorado River near CO - UT stateline | Bitter Creek Well, CO | 39.13276 | -109.0271 |
| **09261000** | Green River near Jensen, UT | | 40.40941 | -109.2354 |
| **09144250** | Gunnison River at Delta, CO | North Delta, CO | 38.75304 | -108.0784 |
| **09379500** | San Juan River near Bluff, UT | Mexican Hat, UT | 37.15068 | -109.8667 |
| **09306290** | White River below Boise Creek, Near Rangely, CO | | 40.17969 | -108.5654 |
| **09260050** | Yampa River at Deerlodge Park, CO | Indian Water Canyon | 40.45163 | -108.5251 |

### 3.2 Metacommunity Diversity and Partitioning

There are a number of ways beta diversity and partitioning can be calculated that are either incidence-based or abundance-based (Legendre & Caceres, 2013). Abundance datasets for each fish species at each location and each year of the program was derived from the STREAMS database. The partitioning method used for this study uses the (Baselga, 2017) guidelines for partitioning absolute abundance-based data using Bray-Curtis dissimilarity coefficients, where the balanced variation in abundance between multiple sites is taken as a replacement metric and abundance gradients in which one assemblage is a subset of another is a metric for nestedness or richness. This study calculated a temporal variation of this method by utilizing consecutive years in the place of multiple sites to calculate fish community dissimilarity across time rather than space using the *betapart* package in R (Baselga, et al., 2021).

The flow regime and fish beta diversity datasets were then matched and a final selection of six sites were made for which there was consistent and significant data between the years 1987-2019. Finally, the local contributions to beta diversity, including the partitioned attributes, were plotted and a non-parametric Kruskal-Wallis one-way ANOVA test was implemented to get a pairwise comparison estimate of significant differences between sites.

### 3.3 Management Interventions

For this analysis, archival data from the UCREFRP program website was extracted for this analysis. The Program Annual Briefings and the Recovery Implementation Program Recovery Action Plan (RIPRAP) documents are available for each year from 1992-2020. Key text pertaining to yearly actions was coded under the following categories:

(1) Text associated with program policy

(2) Text associated with program agenda

(3) Text associated with specific program actions

(4) Text associated with challenges faced during implementation

The UCREFRP has multiple goals including protecting sufficient instream flow to support self-sustaining populations of endangered fish species, providing or enhancing habitat for rare fishes through habitat development or management measures such as fish passageways and backwater habitat development, produce a sufficient supply of hatchery reared fish to support research and recovery activities, collecting critical information on the life history and habitat needs of endangered fish, minimizing the impact of nonnative fishes and incidental take associated with sport fishing on endangered fishes and promoting public understanding and support for efforts to recover endangered fish species (UCREFRP, 1992). These program goals were categorized as shown in Table 2 below.

**Table 2. 2:** Categories Coded for Presence or Absence of Interventions Using Text.

| Action Category | Action Sub-categories |
|---|---|
| **Hydrological (H)** | Legal flow protection |
| | Water acquisition |
| | Designing flows through coordinated reservoir reoperation |
| | Supply augmentation through storage enhancements |
| | Flow studies |
| **Technological (T)** | Fish passages and screens in diversions |
| | New hatchery construction |
| | Hatchery enlargement and operations |
| | Implementing water use efficiency measures |
| **Ecological (E)** | Habitat restoration in floodplains and through acquisition |
| | Endangered fish stocking |
| | Invasive containment through mandatory kill, chemical containment etc. |
| | Research and development and monitoring |

Once these were entered for the period mentioned, the text was coded for the presence or absence of specific actions implemented that were categorized into hydrological, technological and ecological interventions to meet the program goals. Each of these categories were further divided into sub-categories based on the listed range of actions displayed in program documents. These presence-absence values across years were summed up by category to arrive at a final yearly categorical intervention. These values were then matched with flow regime and fish datasets to assess key predictor variables for fish beta diversity.

### 3.4 Models Used

The final dataset comprising beta diversity by year, NAA for each site, and the three summed categories of interventions were then run through a stepwise multiple regression model was conducted to assess which predictors and combination of predictors yielded better results. For a finer grained analysis and attributions of predictor variables for specific year variations in beta diversity, the complete category of predictors was held constant and a generalized linear mixed model was run to identify which years in each site showed the most statistically significant variations. The unique sum of categorical interventions was used as a marker to identify the specific year it was implemented. The parsed text from those years were utilized to attribute specific interventions to the beta diversity in that year. Because one-year community dissimilarity indices were used, the model does not account for effects of an intervention beyond a year and qualitative attribution is used.

### 3.5 Analysis of Management Action Typologies

A final step of this study is to assess whether or not adaptive management is effective and ecological resilience is achieved through program interventions. In order to assess this in accordance with the various resilience and adaptation typologies discussed in the introduction section, the program actions and goals that have been undertaken to date are assessed based on a scale that situates the program within the trend of a broader assessment of conservation actions across landscapes that was conducted (St-Laurent, et al., 2021).

The different typologies have clearly defined actions and primary objectives. While the R-R-T scale was used in a meta-analysis of conservation planning initiatives broadly, it is also a useful tool to situate the actions and goals of specific conservation and restoration initiatives within the broader biophysical and anthropogenic stressors and clarify whether the adaptive management paradigms are effective or even appropriate given the contextual factors.

## 4. Results

Local contributions to beta diversity (LCBD) shown in Figure 5.1, display considerable variation over time across sites especially for the period 2010 to present. This variation is also evident in the partitioned nestedness coefficients where the between-site contributions show greater differences than that for total beta diversity. The turnover component showed the least variation overall except for the San Juan river site. For total beta diversity, independent Kruskal-Wallis one-way ANOVA tests (Kruskal-Wallis chi-squared = 17.993, df = 5, p-value = 0.003) showed the most statistically significant pairwise dissimilarities occurred in the Gunnison-Colorado (K-W = 42.214, p = 0.017) and Gunnison-Green (K-W = 45, p = 0.008) indicating that community dissimilarity patterns are quite different between the two sites. These same patterns are also found when nestedness is tested (Kruskal-Wallis chi squared = 24.702, df = 5, $p < 0.001$) with similar patterns on Gunnison-Colorado (K-W = 56.872, p = 0) and Gunnison-Green (K-W = 48.089, p = 0.005). Testing for the turnover component (Kruskal-Wallis chi-squared = 13.570, df = 5, p-value = 0.019) did not yield any statistically significant pairwise differences.

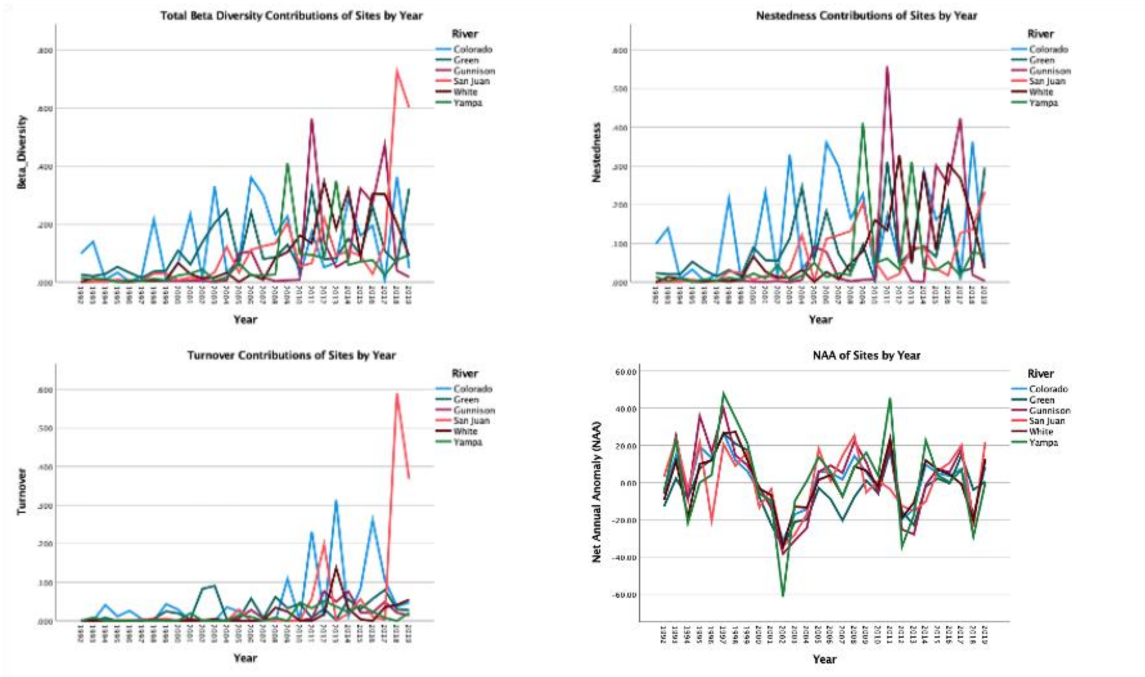


**Figure 2. 3:** Total and Partitioned Beta Diversity Metrics as well as NAA Over Time for Six Selected Sites.

The stepwise regression model utilized NAA within rivers and hydrological, technological and ecological interventions as predictors to assess temporal beta diversity distribution patterns. Table 3 shows the model runs and key statistics, partitioning for various predictor variables. It can be seen that model 1 or NAA by itself is the weakest predictor of beta diversity, while model 8 or the combination of hydrological and technological interventions is the strongest predictor. Most significant is the fact that model 10 and 11 results reinforce the notion that NAA is not a significant predictor of beta diversity. The implication is that the natural flow regime by itself has little to no effect and that interventions such as coordinated reservoir reoperations, flow design and augmentation as well as technological connectivity facilitation and hatchery breeding programs are much more effective. It is also significant to note that hydrological or technological interventions alone were not as strongly predictive as the combination of the two interventions. Furthermore, model 4 results when compared to models 2 and 3 suggest that biotic interventions were not as strongly predictive than those of an abiotic nature. Model 7 results suggest that combination of a natural flow regime and ecological interventions is least predictive of the 2-way model runs. However, model 15 results are statistically significant and indicate that hydrological and technological interventions buffer the significance of NAA and ecological interventions.

**Table 2. 3:** Summary of Model Runs Results.

| No. | Model | Akaike's Information Criterion (AIC) | Bayesian Information Criterion (BIC) | df | F | p |
|---|---|---|---|---|---|---|
| 1 | NAA | -215.40 | -206.04 | 1-166 | 0.091 | 0.760 |
| 2 | Hydro | -220.74 | -211.37 | 1-166 | 5.446 | 0.021 |
| 3 | Tech | -220.19 | -210.82 | 1-166 | 4.887 | 0.028 |
| 4 | Eco | -218.84 | -209.47 | 1-166 | 3.523 | 0.062 |
| 5 | NAA*Hydro | -218.83 | -206.33 | 2-165 | 2.750 | 0.067 |
| 6 | NAA*Tech | -218.19 | -205.70 | 2-165 | 2.429 | 0.091 |
| 7 | NAA*Eco | -217.10 | -204.61 | 2-165 | 1.879 | 0.156 |
| 8 | Hydro*Tech | -224.05 | -211.55 | 2-165 | 5.442 | 0.005 |
| 9 | Hydro*Eco | -220.22 | -207.72 | 2-165 | 3.461 | 0.034 |
| 10 | Tech*Eco | -221.94 | -209.44 | 2-165 | 4.344 | 0.015 |
| 11 | NAA*Hydro*Tech | -222.05 | -206.43 | 3-164 | 3.607 | 0.015 |
| 12 | NAA*Hydro*Eco | -218.41 | -202.79 | 3-164 | 2.357 | 0.074 |
| 13 | NAA*Tech*Eco | -219.97 | -204.35 | 3-164 | 2.888 | 0.037 |
| 14 | Hydro*Tech*Eco | -223.61 | -207.99 | 3-164 | 4.150 | 0.007 |
| 15 | NAA*Hydro*Tech*Eco | -221.62 | -202.87 | 4-163 | 3.095 | 0.017 |

Pearson's Correlation coefficients showed weak negatively correlated relationships between beta diversity and the hydrological (-0.178), technological (-0.169) and ecological (-0.144) interventions, weak positive correlations between technological intervention and NAA (0.152) and a moderate negative correlation between hydrological and ecological interventions (-0.319). Sigma one-tailed correlations show moderately positive correlations between beta diversity and NAA (0.382), hydrological intervention and NAA (0.470), hydrological and technological interventions (0.375) and ecological and technological interventions (0.434). Finally, the distribution of beta diversity against regression standardized predicted values is shown in Figure 5 below. Significant clustering around low beta diversity values suggest that the predictor variables account for a significant proportion of community similarity across sites. The regression standardized residual values plotted against regression standardized predicted values show a significant amount of heteroskedasticity.

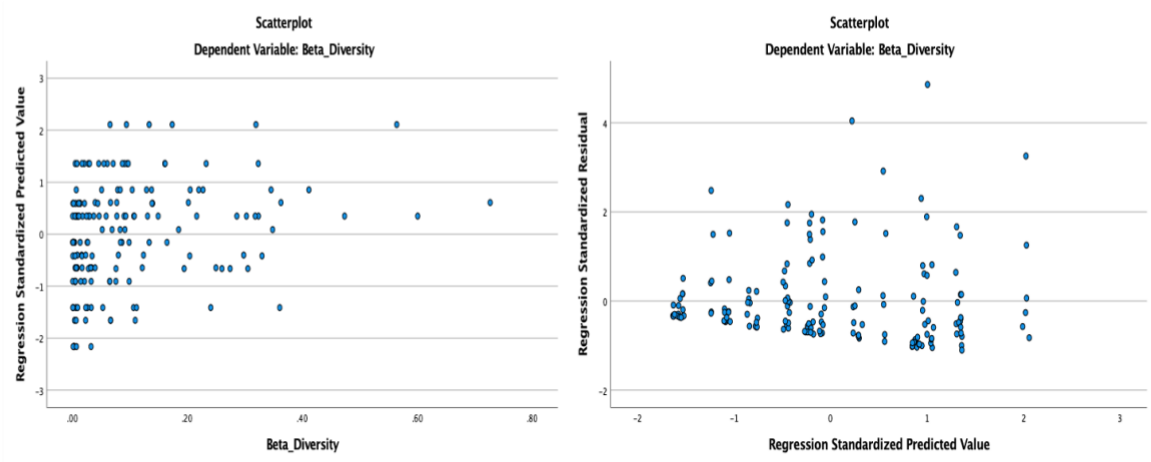


**Figure 2. 4:** Beta Diversity Distribution Patterns After Regression.

The generalized linear mixed model results are shown in Table 4 below. The summed numbers in the hydrological (H), technological (T) and ecological (E) interventions serve as “DNA markers” attributing for the specific year the combination was applicable from the qualitative coding exercise. It can be seen from Table 4 below that specific interventions such as flow regimes, regulations or augmentations have more definite and immediate impacts on fish community assemblages in that same year than the other interventions. Other interventions from technological and ecological categories may not have immediate impacts but may have lagged effects on beta diversity by as much as several years due to dependence on slower biological and ecological responses and processes such as the White River and Gunnison River systems started much later than the interventions on the mainstem Colorado, and Green Rivers. These effects are harder to attribute with the current model and would require different analytical methods in further analysis.

**Table 2. 4:** Statistically Significant Variations in Site-Specific Temporal Beta Diversity.

| Site | Model Term | Year | t | Sig. | Intervention Descriptions |
|---|---|---|---|---|---|
| **Colorado** | NAA*H(0)*T(2)*E(4) | 2018 | -3.378 | 0.003 | Replacement & stocking of non-native, incompatible species with compatible, sterile ones in UT, CO. High invasive removal with extensive public support. |
| | NAA*H(2)*T(1)*E(1) | 1998 | 2.755 | 0.013 | Colorado Water Conservation Board (CWCB) filed year-round instream base & recovery flow rights through Grand Valley. Study on coordinated reservoir reoperations. |
| | NAA*H(2)*T(2)*E(2) | 2007 | 2.603 | 0.017 | Flows were provided for habitat mapping work in the endangered fish critical habitat area and to accommodate razorback sucker and Colorado pikeminnow stocking efforts. |
| | NAA*H(4)*T(2)*E(2) | 2006 | 3.351 | 0.003 | Total of 28,460 acre-ft released through coordinated reservoir reop. Elkhead Dam & Reservoir Enlargement project in NW CO. Funding for 6 hatchery facilities. |
| | NAA*H(5)*T(0)*E(2) | 2003 | -2.984 | 0.008 | Water made available by the leases for release of 10,825 acre-feet/year of water from Ruedi Reservoir and the permanent dedication of 10,825 acre-feet/year from Colorado Water Division Number 5 facilities to be delivered and protected to the 15-mile reach during the late summer period. Colorado River Water District (CRWCD) and Denver Water delivered 5,412 acre-feet of water from Wolford Mountain and Williams Fork reservoirs. Additional water being provided by CRWCD for delivery of up to 6,000 acre-feet of water from Wolford Mountain Reservoir. |
| | NAA*H(0)*T(0)*E(3) | 2011 | 2.857 | 0.010 | Draft of UCRB Nonnative and Invasive Aquatic Species Prevention and Control Strategy. |
| **Green** | NAA*H(2)*T(1)*E(2) | 2019 | 2.910 | 0.009 | Preliminary estimates of Colorado pikeminnow abundance for the Green River show a continued decline for the species in this basin. Partners are experimenting with the timing and magnitude of base flows, as well as continued nonnative fish management, in an effort to increase survival of fish in their first year. |
| | NAA*H(4)*T(1)*E(3) | 2016 | -2.150 | 0.045 | A Larval Trigger Study Plan (LTSP) is being implemented for an experimental period of ~ 6 years beginning in 2012. The USDA Natural Resources Conservation Service (NRCS), along with state and local partners, began rehabilitating the Tusher Wash Diversion Dam on the Green River in the winter of 2015 to design a barrier to prevent endangered fishes from |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | entering and becoming trapped in the Green River Company Canal. To provide additional habitat for young razorback sucker under the LTSP, the U.S. Fish and Wildlife Service (USFWS) completed a wetland enhancement project at Johnson Bottom on the Ouray Refuge in spring 2015. |
| **Gunnison** | NAA*H(0)*T(0)*E(3) | 2011 | 5.782 | <0.001 | |
| | NAA*H(0)*T(1)*E(3) | 2010 | 2.899 | 0.009 | In 2010, the programs focused on the importance of developing a long-term commitment to prevention in their Nonnative Fish Management Strategies as well as a re-commitment to focusing control actions at the sources (spawning areas) of these problematic nonnative fish species. Long-term selenium contamination clean-up is being carried out independent of the program. |
| | NAA*H(2)*T(1)*E(3) | 2017 | 4.699 | <0.001 | |
| | NAA*H(4)*T(1)*E(3) | 2016 | 2.320 | 0.032 | Colorado Parks & Wildlife (CPW) implemented an unlimited harvest of smallmouth bass. Tri-County Water has avoided using the spillway since 2014, when the problem of smallmouth bass escapement was recognized. |
| **San Juan** | NAA*H(0)*T(2)*E(4) | 2018 | -7.725 | <0.001 | Colorado pikeminnow are being reestablished in the San Juan River. 2,912,113 Colorado pikeminnow have been stocked in the San Juan River between 2011 - 2017. The number of stocked Colorado pikeminnow captured during monitoring projects increased in 2017. |
| | NAA*H(2)*T(1)*E(2) | 2019 | 6.219 | <0.001 | |
| **White** | NAA*H(1)*T(1)*E(4) | 2012 | -3.171 | 0.005 | In spring 2011, while sampling for Colorado pikeminnow in the White River, researchers found razorback sucker in spawning condition. In June, researchers collected razorback sucker larvae in White River backwaters confirming spawning occurred in this river. The recovery programs are revising stocking strategies for razorback fish survival. |
| | NAA*H(2)*T(1)*E(3) | 2017 | -2.662 | 0.015 | A White River management plan was to be drafted in 2016-17, to ultimately serve as the basis for a White River programmatic biological opinion. This management plan aimed to include flow recommendations. |
| | NAA*H(4)*T(1)*E(3) | 2016 | 2.690 | 0.015 | |
| **Yampa** | NAA*H(1)*T(1)*E(3) | 2009 | 3.958 | <0.001 | A five-year lease for water from Steamboat Lake was completed in 2005 with Colorado State Parks to support late-summer target flows in the lower Yampa River. Catch of age-0 Colorado pikeminnow in the upper reach of the Green River has been very low and of particular concern to researchers since |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | the mid-1990s. Catches in that reach increased in 2009, presumably due to higher flows in 2008 and 2009 as well as other recovery actions like nonnative fish management. |
| | NAA*H(4)*T(0)*E(0) | 2013 | -3.205 | 0.005 | |

(AIC = 670.5, BIC = 671.2.)

It can also be seen that most statistically significant beta diversity effects appear in post-2000 years and most specifically over the last decade. What is not reflected in the beta diversity effect is whether the community dissimilarity reflects greater diversity in native community structure that may be a beneficial effect or the presence of invasive species that may be a detrimental effect. This lends credence to the implication that abiotic interventions specifically targeted to disrupt key life history points of invasive species do not always work. The 2011 shift in program focus to long-term invasive species containment reflects the fact that while hydrological and technological interventions have proven successful in maintaining beta diversity, abiotic interventions can only go so far, and the threat of invasive species is of greater moment going forward. While the importance of and investment in hydrological and technological interventions is maintained in the post-2011 period, there is a greater shift toward interventions focusing on preservation of a favorable biotic environment for endangered fish species.

Characterizing the UCREFRP against the adaptive management paradigm requires not just listing the program goals and actions against the various components of adaptive management but also an understanding of what internal and external stressors are at play. Figure 5 below depicts where in the spectrum of adaptive management the program goals fall.

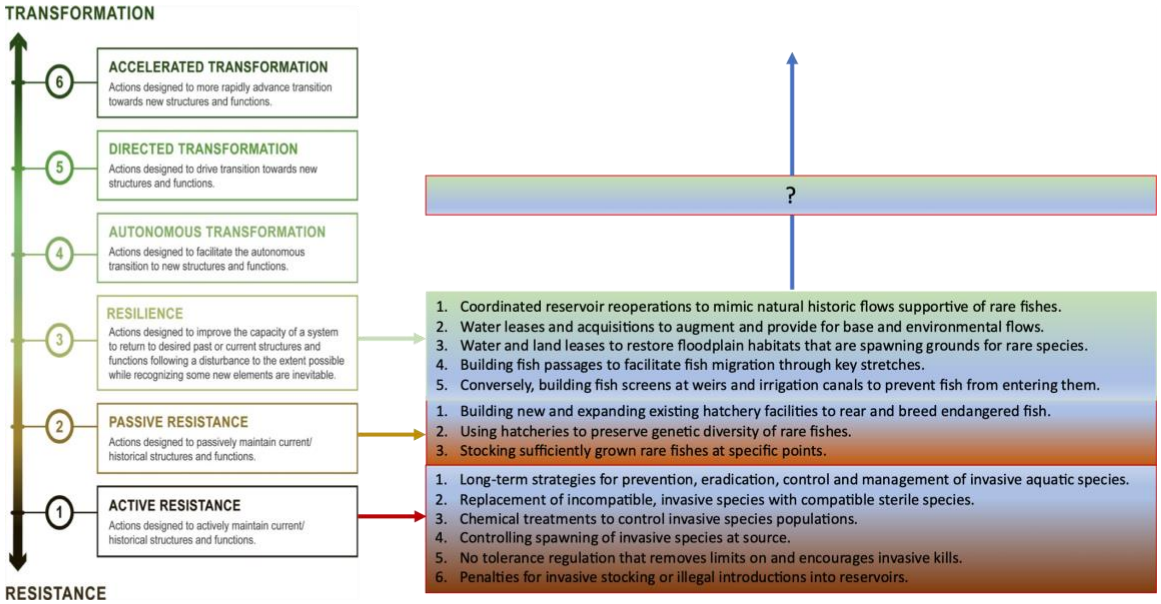


**Figure 2. 5:** Program Policies and Actions as Translated into Adaptation Paradigms.

**Source:** Adapted from (St-Laurent, et al., 2021).

In the 30-year timeline of the program from 1987-2020, considerable capital investment and efforts went into provision of base and restoration flows in the early and through the mid-years of the program duration. This entailed utilization of legal means, financial provisions for sustainability, conducting flow studies and coordinated reservoir reoperations, acquiring water leases for flow augmentation, and land leases for floodplain restoration, as well as working on rebuilding connectivity into the system through building fish passages. Concurrently, early and mid-duration periods also saw substantial investment into hatchery construction and expansions to breed and stock endangered fishes. Since 2011, as the capital investments and construction projects wound down and as water lease acquisition as a tool was fully utilized, the focus has shifted toward the ever-growing threat from invasive species.

We can therefore see the shift in program focus over the duration of the program from initial actions to build resilience through habitat provision and other abiotic interventions toward passive resistance mid-duration and subsequently, more active resistance strategies in the past decade in invasive management. The UCREFRP goals were to balance water development and conservation interests. But a backsliding in program strategies from initial resilience building to resistance strategies to battle against invasive species shows that in terms of both current and future water development initiatives and effectiveness of current strategies toward active conservation and restoration of endangered species, the biophysical limits of the system capacity to respond meaningfully and in a goal-directed way have been reached.

## 5. Discussion

One of the biggest questions in endangered species recovery following interventions is whether the interventions are effective and to what degree are they effective? This ties back to the first key question of the research study that seeks to uncover the determinants of recovery program success. The implication built into this is that the program has been successful. The results show that the success is relative, limited and contingent on a host of factors. Below, we investigate the predictive factors of program success as well as whether ecological resilience has been achieved through program implementation. Finally, we discuss whether adaptive management has been effective in the context of the program.

### 5.1 Impacts of Recovery Actions on Species of Concern

This study analyzed the impacts of a series of predictor variables on community dissimilarity or beta diversity indices. The predictor variables included NAA as an indicator of natural flow regime variability and specific management interventions of hydrological, technological and ecological categories as indicators of anthropogenic variations. There is a very specific distinction made between the inclusion of NAA and hydrologic interventions as a predictor variable. NAA for the Upper Basin river system refers to natural or regulated flows along the main stem depending on the degree of development. Hydrologic interventions feature purposely designed flows to mimic the natural flow regime in order to create conducive abiotic environments for species of concern as well as to disrupt the life stages of harmful invasive species. This distinction allows us to see that the natural flow regimes by themselves, even dampened, have little to no impact on community dissimilarity across space and time, and it is only in conjunction with specific management interventions that program success was achieved.

The combination of hydrological and technological interventions was key to program success. The major hydrologic interventions accomplished over time were the implementation of design flows through coordinated reservoir reoperations which started with preliminary studies since 1992 on modification of operations of the Flaming Gorge and Aspinall Unit dams to mimic the natural temperature and flow regimes of the Green River and also the Navajo reservoir for the San Juan River Recovery Implementation Program that same year. Other strategies included purchasing of water rights Concurrently, large capital investments in constructing fish passages and ladders at Taylor Draw Dam on the White River, at the Redlands Diversion Dam, the Price-Stubb Dam, the Government Highline Dam and several low-height agricultural diversion dams along the Yampa River. This facilitation of connectivity at several locations on the Yampa, Gunnison and Colorado Rivers through technological interventions as well as hatchery construction and stock breeding have made it a strong secondary predictor of community similarity after the hydrological interventions.

Ecological interventions such as floodplain restoration and habitat protection have been successful, though other measures such as rare fish stocking and invasive containment through harvest and chemical containment have been much less successful, making it a weaker overall predictor of community similarity. Invasive containment strategies have suffered several setbacks and the long-term containment strategy reflects the long-term nature of this intervention. There is some overlap between hydrological and ecological interventions because the design flows are also intended to disrupt life history stages of invasive species and this had met with limited success. Ecological interventions are the most complex because they are intended to balance between the need for rare species preservation and growing recreational fishing popularity that drives stocking of invasive species no less. Invasive stocking strategies are being reconsidered to contain harmful species and push more rare species-compatible invasive fish species including sterile phenotypes of harmful species. In this context, it can be seen why ecological interventions are much less successful.

### 5.2 Ecological Resilience

It can be seen from Figure 5 that a lot of the UCREFRP program strategies and actions are designed to maintain historic conditions, species and populations to a certain extent while balancing for development and recreational use demands on the river. The multitude of strategies, both through biotic and abiotic containment, are designed to actively resist transformation of the river community structures and preserve endangered fish species in compliance with the ESA. More passive resistance strategies also include the utilization of hatchery models to preserve the genetic diversity of historical broods.

Within the adaptive management paradigm, ecological resilience strategies have been more of an abiotic nature including flow design through coordinated reservoir reoperations and connectivity facilitation. We can conclude that resilience of rare fish populations has been partially achieved through these interventions, though the precarious nature of it is demonstrated by the creeping uncontrollability of biotic interventions and invasive species presence in the system. Furthermore, the compounding effects of climate change and prolonged drought are redefining water use legally and socio-economically for the entire Colorado river system. These call for a rethink of current program management paradigms and a broader look at what achieving system resilience entails long-term, and what it would mean to reduce resistive strategies and incorporate transformability into the system to improve resilience.

### 5.3 Adaptive Management Paradigms

To understand the implications of this, we circle back to Figure 1 where controllability of factors and uncertainty determine the proper management paradigm to utilize. The UCREFRP was developed in 1987 as a response to legal and punitive sanctions that incentivized endangered species conservation. Long-term program maintenance has been the result of significant tangible and intangible investments toward direct and indirect conservation measures. The management paradigm remains the same today as it was in 1987 when key stressors such as climate change were not yet in the global consciousness. Therefore, in terms of controllability, the key factors that could be controlled to a high degree were flow regimes, water allocations and endangered fish numbers (through hatchery stocking programs). The high uncertainty in the system was a consequence of limited scientific knowledge and understanding of whether these measures would result in the establishment of self-sustaining populations of endangered fish species. Therefore, adaptive management practices where flow studies were conducted and species and community-specific responses were studied was the appropriate paradigm for utilization through the 1990s to early 2000s. However, since

2000 the United States Southwest has been in the grip of an extended drought period that has resulted in massive shifts in the way water is used and conserved.

Drought is a complex natural hazard that impacts ecosystems and society in multiple ways. There is currently no universal definition of drought, and the simplest definition is that it is a deficit of water compared with normal conditions. What conditions constitute normal is dependent on the ways in which water is used (Van Loon, 2015). Drought characterizations in arid regions are particularly challenging. Drought definitions are categorized into four main measurable categories: meteorological, hydrological, agricultural and socio-economic (Wilhite & Glantz, 1985). The first three approaches pertain to drought as a physical phenomenon, while the last approach is a measure of the cascading impacts of drought on socio-economic systems. Droughts also differ from each other in three essential characteristics – intensity, duration and spatial coverage (Wilhite, 1983).

Most drought definitions to date that encompass the various measurable categories view it from a human-centric lens and do not fully address the ecological dimensions of drought (Crausbay, et al., 2017). Climate change is also expected to increase the likelihood of multidecadal droughts. The sensitivity and adaptive capacity of ecosystems and species to ecological drought are also driven by interactions between natural and human systems, the severity of which can range from small-scale temporary responses (e.g. reduced productivity or increased dehydration stress in wildlife) to widespread and persistent ecosystem transformations (e.g. vegetation type conversion or species range shifts) (Crausbay, et al., 2017). Decomposition of ecological drought especially in the context of anthropogenic climate change has revealed various types of droughts including snow drought (including dry snow drought and warm snow drought), hotter droughts (accounting for the effects of temperature increases), flash droughts (which are sudden onset and rapid intensification of drought conditions with severe impacts) and megadroughts (lasting for at least two decades) (Crausbay, et al., 2020).

Global warming has pushed what would have been a moderate drought in southwestern North America into megadrought territory (Williams, et al., 2020). The United States Southwest has been in the grip of an extended drought with concerns that the trend is towards increasing aridification rather than a return to historic conditions (Overpeck & Udall, 2020) making a drought classification moot. The Colorado River Basin has over the past 20 years utilized a number of legal, economic and policy tools such as water trading (Howe & Goemans, 2003); (Wildman Jr. & Forde, 2012); (Ghosh, 2018), water shortage risk sharing through the Colorado River Interim Guidelines developed in 2007 and voluntary water cutbacks through the Colorado River Drought Contingency Plan signed in 2019.

### 5.4 Future Pathways

Within this framework, and the context of episodic hydrologic drought in the years 2002, 2012 and 2018, we observe that the UCREFRP did not face challenges in securing water for environmental flows during the 2002 hydrologic drought. By the time of the 2012 drought within the context of the 19-year extended drought period, all water leases, flow augmentations, coordinated reservoir reoperations had already been codified within the Program operational paradigm and no further modifications were viable nor planned while accounting for use on the river. And climate change is just one of the numerous stressors on the Colorado river system.

Anthropogenic stresses in the form of altered flow regimes has resulted in detrimental impacts on stream biotic communities (Kennedy, et al., 2016); (Tonkin, et al., 2017); (Ruhi, et al., 2018); (Kominoski, et al., 2018). While connectivity provision has been implemented to aid endangered fish recovery, a high degree of uncertainty exists around whether or not stocked fish life history strategies are adapting rapidly enough to the compounded effects of both anthropogenic use and climate change. While the current endangered and other native species have life history strategies that have made them adaptable to historic flow regimes, including during periods of historic drought, consideration of future-adapted species rather than past-adapted species, especially in altered systems is called for. Future-adapted species characteristics at the individual and population levels include tolerance, plasticity, avoidance, and genetic/phenotypic variability (Crausbay, et al., 2020).

The UCREFRP has built its entire hatchery stocking program around the preservation of the genetic diversity of endangered native fish species and to provide supplemental stocks for replenishment. However, there is a need to look into how to manage the system to facilitate species adaptations beyond even drought-tolerance to increased aridification. The compounded effects of these stressors cannot be controlled for, and this is where, according to Figure 1, the adaptive management paradigm of the program with its focus on a maintenance of some level of historic conditions falls short.

The high degree of uncontrollability and the high level of uncertainty calls for a strategy toward building resilience where possible, but really moving more toward scenario planning for altered futures. Preliminary studies on scenario planning have already been conducted (Bestgen, et al., 2020). However, these need to be expanded to not only consider sub-basin level scales but a range of combined social-ecological futures that feature the differential nature and severity of impacts on socioeconomic systems and ecosystems together. Operationalizing this using the R-R-T scale is possible but requires a multi-stakeholder initiative and a visualization of the river ecosystem as a comprehensive social-ecological-technical system (SETS). The trade-offs in conservation and restoration planning paradigms is no longer how to balance priorities between water development and environmental conservation purposes, but how to buffer a greatly altered SETS against the varying pressures it faces by building transformability into adaptive management programs. This requires navigating the attendant tensions between engineering resilience which seeks system stabilization and ecological resilience which seeks system persistence.

## PART III: A SOCIAL-ECOLOGICAL SYSTEMS LEVEL CLINICAL DIAGNOSIS OF COLORADO RIVER SUB-BASIN RECOVERY PROGRAMS

### 1. Introduction

Living within ecological boundaries of our biosphere (Rockström, et al., 2009) while ensuring the sustainable and equitable use of its natural resources is one of the biggest challenges facing humanity in the present century. Rivers serve as the chief source of renewable water supply for humans and freshwater ecosystems (Vörösmarty, et al., 2010) and water scarcity is a global threat to both society and to freshwater biodiversity (Ruhi, et al., 2016). The impact of water scarcity accentuates the incident threat to human water security and biodiversity especially in drylands and desert belt transition zones across continents (Vörösmarty, et al., 2010).

This scenario is particularly accentuated for the western United States where Manifest Destiny and a favorable hydroclimate led to the establishment of a significant agricultural economy, especially in the southwest, despite the warnings of early naturalists like John Wesley Powell (Sabo, et al., 2010). Concern over water quality and quantity, biodiversity and land preservation along rivers has led to a boom in restoration activity across the United States at an annual cost of roughly $1 billion (Bernhardt, et al., 2005). River restoration in the U.S. Southwest has followed national trends to a large degree but has also been shaped by influences unique to the region (Follstad Shah, et al., 2007).

Previous system-scale studies of river basins have utilized panarchy theory or Ostrom's social-ecological systems (SES) framework to assess the resilience of river basin systems in various ways. One of the premier examples of the application of a SES framework in river basin resilience assessment was that by Cosens & Fremier (2015) where the

Columbia River Basin resilience was traced through historical timelines divided into pre-contact, post-contact, dam-building and civil and environmental justice eras. The article presents eyeball estimates of ecosystem services present in the Columbia River and then uses expert elicitation to quantify resilience based on defined resilience metrics. This has been an often-used method in other case studies using panarchy theory and other resilience related assessments in adaptive governance of river basins (Allen et al. 2018, Cumming 2011, Nemec et al. 2014). While this method is a proven technique, it draws attention to the underlying problem of insufficiently incorporating widely-available ecological metrics into SES analyses, that may obviate the need for eyeballing and estimating resilience and bring more exactitude in resilience measurements.

The common tendencies of SES analyses to be all-encompassing and include integrated analyses of SES systems often results in an overemphasis on institutional aspects and governance regimes and very little emphasis on ecology. To the extent that biophysical attributes are described at all in commonly used frameworks such as IAD, SES and robustness frameworks among others, attribute descriptions tend to be limited to resource unit mobility, resource system productivity, clarity of system boundaries and size of the resource system. Furthermore, these variables are considered only as they relate to the action situation, ignoring the potential contribution of biophysical processes to the system (Epstein et al. 2013, Vogt et al. 2015). While there is a call from the social sciences to incorporate more "Ecology" into SES analyses, there is simultaneously, a call from the ecological and biophysical sciences to incorporate more social science and human aspects into management and decision-making of river systems (Poff et al. 2003, Martin Labadie & Poff 2015).

The aim of this study is to bridge the gaps in system-level river basin resilience assessments and offer an alternative approach that brings ecology more into the forefront. The framework used is described in section 1.1. This study builds on the principles of SES and CASS principles to assess adaptive governance in river restoration programs in the arid Southwest, in particular, the Colorado River Basin to answer the following questions:

(1) ***To what extent do basin-scale restoration programs contribute to system resilience of the Colorado River?***
(2) ***What is the social and ecological fit and what trade-offs emerge when balancing development and conservation interests in such restoration programs?***
(3) ***What are the opportunities for a transformative pathway going forward?***

The study analyzes the evolution and performance of the basin-scale mitigation and restoration programs – the Upper Colorado River Endangered Fish Recovery Program (UCR-EFRP) and the Lower Colorado River Multi-Species Conservation Program (LCR-MSCP).

## 1.1 Adaptive River Governance

The evolution of river governance followed a distinct pattern starting with being conceptualized as water resource systems (WRS) in the 1960s where the focus was on decision support by following a normative (optimization) route that still persists today (Brown, et al., 2015; Kasprzyk, et al., 2018), then followed by an integrated water resources management (IWRM) framework introduced in the 1990s and geared toward actual implementation by involving integration across the entire hydrologic cycle, accommodating different water users and including engineering, economic, social, ecological and legal aspects, while accounting for multiple spatial scales and upstream/downstream perspectives (Global Water Partnership, 2009); and finally to the much more recent development of interdisciplinary frameworks exploring the mutual shaping of society and nature including as social-ecological systems (SES), coupled human-nature systems and complex adaptive systems science (CASS) (Baldassarre, et al., 2019).

Resilience is defined as the capacity of a system to absorb disturbance reorganize while undergoing change so as to retain the same structure, function, identity and feedbacks (Walker, et al., 2004). In the context of social-ecological systems, management of ecosystem resilience requires the ability to observe and interpret essential processes and variables in ecosystem dynamics to develop the social capacity to respond to environmental feedback and change (Carpenter, et al., 2001). Because the self-organizing properties of complex ecosystems and associated management systems seem to cause uncertainty to grow over time, understanding should be continuously updated and adjusted, and each management action viewed as an opportunity to further learn how to adapt to changing circumstances (Carpenter & Gunderson, 2001).

A leading approach to successfully meet the challenges of changes in social-ecological systems is adaptive governance (Koontz, et al., 2015). Adaptive governance is defined as "changing rules and norms from a static, rule-based, formal and fixed organization with clear boundaries" to a view of institutions as "more dynamic, adaptive and flexible for coping with future climatic conditions" (IISD, 2006). Governing complex adaptive ecosystems requires adaptive managers supported by flexible organizations, problemoriented organization, networks of collaboration at all levels and across levels and leadership.

Institutions governing multi-species resource commons should optimize the turnover and use of extractables without compromising the functional aspects of the ecosystem. This can be achieved by implementation of rule systems that maintain the diversity that sustains a multitude of species. Scarce resources and diverse demands predict institutions with some form of strict protection of the habitat that supports the scarce biota (Becker & Ostrom, 1995).

In the context of River Basin Organizations (RBOs), a diagnostic framework to analyze complex policy situations and their coevolution with ecosystem effects calls for functional process interactions and mutual dependencies at basin-scale within and between the social-institutional and biophysical systems of the basin (Bouckaert, et al., 2018). RBOs are traditionally focused on holistic demand management based on IWRM principles and RBO institutions have been clearly defined and conceptualized based on criteria including the presence of international water treaties, institutionalization of cooperation, specific governance mechanisms and a list of other factors (Schmeier, et al., 2016).

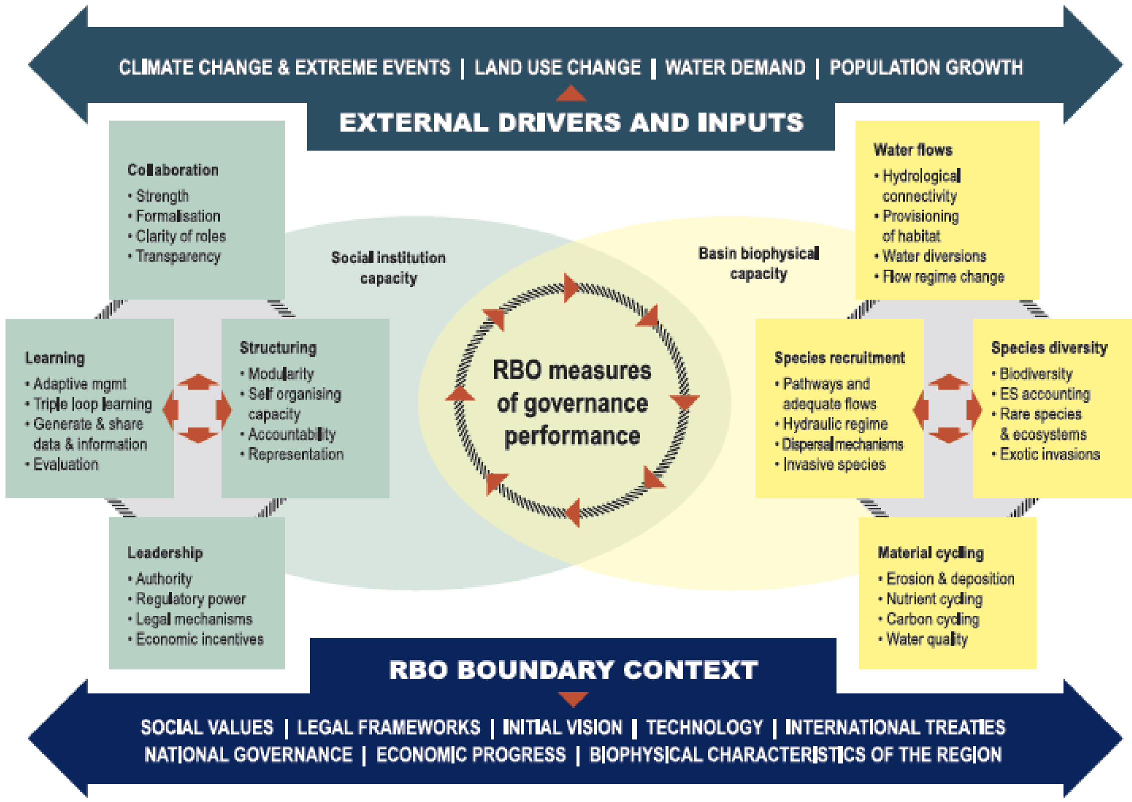


**Figure 3. 1:** A Diagnostic Framework for Assessing RBO Capacity for Sustainable River Governance (Bouckaert et al., 2018).

The UCR-EFRP and LCR-MSCP programs along the Colorado River do not strictly classify as RBOs as they are focused on balancing demands on the river with restoration and maintenance of aquatic and riparian health. However, a reconstitution and expansion of the institutional architecture of the Law of the River, that legalized Colorado River flow entitlements to various Basin States and Mexico, is still a basin-scale organization with a different institutional vision. With this in mind, Figure 1 illustrates the dynamic interplay of the institutional and ecological processes and their co-evolution that characterizes the system state and trajectory. This framework is a reconstitution, within a specific river basin context, of a broader framework for assessing fit between ecosystem characteristics and regime variables in terms of stock, flows, controls and resilience among others (Young, 2002).

Adaptive governance is operationalized by adaptive co-management, with the latter representing a suite of nested processes including collaboration and learning associated with specific resource management objectives, without which adaptive governance could not function (Folke, et al., 2005). Co-evolutionary processes as a structural feature of a water governance system are largely missing in frameworks (Bouckaert, et al., 2018). Analyses of two separate components in a complex adaptive system such as a river basin can yield insights into the factors that independently affect institutional resilience as well as ecological resilience. However, to really assess system-level social-ecological resilience, the two separate components and the feedbacks between them must be looked at as a co-evolving system. Figure 1 breaks down each system into irreducible, complementary and co-dependent components that can influence each other in non-linear ways.

The Bouckaert et al (2018) framework makes parallels between corresponding social and biophysical elements by for example, categorizing collaboration and water flows as connectivity elements, structuring and species diversity as assemblage of elements in the social and biophysical systems respectively and so on. They then use a rating system of social and biophysical elements to chart the trajectory of river basin governance over time much like the panarchy theory is utilized for. This study argues that the strength of the framework is not in scoring system elements but using measurable descriptions (either qualitative or quantitative, as appropriate) of social and biophysical elements to score system properties that they constitute and arrive at a state of the system across time with a clear indication of trade-offs (defined as the distance between scored social and biophysical indicators for that system property).

The system properties are broadly categorized into system architecture and system dynamics and building on the Bouckaert et al (2018) study, the following system properties and constituent elements are identified:

(1) System architecture: Connectivity and Distribution – Collaboration as social and water flows as biophysical indicator.
(2) System architecture: Assemblage of Elements – Structuring as social and species diversity as biophysical indicator.
(3) System dynamics: Social and Natural Capital – Leadership as social and material cycling as biophysical indicator.
(4) System dynamics: Renewal and Continuation – Learning as social and species recruitment as biophysical indicator.

## 2. Methods

Each of the four subsequent sections, that describe the system architecture or dynamics properties, start with a conceptual foundation for the specific indicator being discussed. The first paragraph introduces the social/institutional conceptual background and the second paragraph in that section introduces the biophysical conceptual background. This is then followed by 2 subsections that diagnose the two Colorado River recovery programs, in order, on institutional and biophysical performance, respectively. The diagnostic method utilized is described in Table 1 below (with a detailed explanation of derivation of metrics in Appendix B).

Changes in hydrologic connectivity patterns will affect the water cycle and consequently, the regulatory capacity of the river (Gao , et al., 2018), making connectivity a significant metric of assessment for system architecture. Dams have significantly altered natural flow dynamics, with changes in natural flood pulse dynamics having altered assemblage structures of aquatic communities significantly (Ngor, et al., 2018), making both governance and species assemblage also important assessment metrics for system architecture.

While it is accepted that humans are part of the environment, it is not always recognized that they perform multiple roles as coproducers of ecosystem services, as beneficiaries of those services and through the addition of capital to realize those services (Jones, et al., 2016). Ecosystem accounting approaches have tended to separate out the natural capital and human capital elements (Jones, et al., 2016). Here we look at them conjointly as key elements of system dynamics. Furthermore, actions such as environmental flows that mimic pre-development river flows to conserve selected biodiversity, reserving aquatic refugia, construction of fish passages, restoration of riparian vegetation to cool rivers and so on have been categorized as "renewal ecology" initiatives, distinct from conservation ecology or restoration ecology (Bowman, et al., 2017). The coupled human-natural system that embodies aspects of renewal and transformation is, therefore, a key metric of assessment in system dynamics.

**Table 3. 1:** Metrics for Assessing Social and Biophysical Indicators of System Architecture and Dynamics.

| Category | Social | Biophysical |
|---|---|---|
| **Connectivity & Distribution** | 1 - There is no social connectivity/collaboration and a lack of shared interests or considerable conflict.<br>2 – There is little connectivity and little shared interests.<br>3 – There is some connectivity and the beginnings of convergence to a shared vision.<br>4 – There is good connectivity and the presence of a shared vision and resources.<br>5 – The connectivity is excellent and the institutional mission is formalized. | 1 – High levels of gray infrastructure and highly regulated flows over >70% of the river with very little natural habitat remaining.<br>2 – High levels of gray infrastructure and high flow regulation, isolated, fragmented habitat for native species.<br>3 – Moderate to high levels of gray infrastructure with significant flow regulation, but fish passages and effort to protect/restore habitat for native species and prevent fragmentation.<br>4 – Low levels of gray infrastructure with more natural flow regimes and variability supporting aquatic and riparian habitat. Little fragmentation. |

| | | |
|---|---|---|
| | | 5 – Mostly free-flowing river with low fragmentation and no barriers to fish passage. |
| **Assemblage of Elements** | 1 – Functionally distinct expertise with no overlap. Little representation of all affected parties.<br>2 – Functionally diverse expertise with little overlap. Some representation of affected parties.<br>3 – Functionally diverse expertise with redundancy. Moderate representation of affected parties.<br>4 – Significant functional diversity and redundancy and high levels of representation and accountability.<br>5 – Polycentric structure with good representation and accountability. | 1 – Highly altered ecosystem with preponderance of invasive species and extinct / critically endangered native species. Low species diversity.<br>2 – Ecosystem having high levels of invasive species and critically endangered native species. Close to tipping point. Low species diversity.<br>3 – Ecosystem with endangered and threatened native species at a precarious state of co-existence. Moderate species diversity.<br>4 – Ecosystem with some invasive species but still retaining high species diversity and prevalence of native species.<br>5 – Relatively undisturbed system with high species diversity. |
| **Social and Natural Capital** | 1 – Top-down distribution of power / decision-making with “individualist” mindset.<br>2 – Hierarchical structure / power distribution with “competitive” mindset.<br>3 – Top-down structure with “prosocial” mindset.<br>4 – More distributed decision-making with “competitive” mindset.<br>5 – More distributed decision-making with “prosocial” mindset. | 1 – Highly altered/degraded system with very little nutrient cycling. Ecosystem functioning significantly disrupted.<br>2 – Highly altered system with significant disruption of ecosystem processes and limited opportunities for restoration.<br>3 – Significantly altered system with some disruption of ecosystem processes but more options for restoration.<br>4 – Moderately altered system with some disruption of ecosystem processes but high restoration potential.<br>5 – Slightly altered system with ecosystem processes not significantly disrupted and very little need for restoration. |
| **Renewal & Continuation** | 1 – Reactive institution operating in hindsight and not sensitive to feedback.<br>2 – Institution adapts processes and actions based on feedback but no significant learning taking place at policy level.<br>3 – Institution adapts processes and occasionally policies based on feedback but has little adaptive capacity built.<br>4 – Institution is sensitive to feedback and incorporates double-loop learning.<br>5 – Institution operates on a triple-loop learning paradigm. | 1 – Highly fragmented system with different regimes at different points jeopardizing species recruitment and dispersal.<br>2 – High system fragmentation and low dispersal ability. High reliance on technical solutions to prop up degraded system.<br>3 – Moderate system fragmentation with restricted dispersal ability. High dependence on technical fixes.<br>4 – Species recruitment is possible with technical fixes and there is little need for extreme measures such as stocking and artificial transport.<br>5 – High species recruitment and dispersal ability because of low anthropogenic system demands. |

The social/institutional and biophysical descriptions for the two recovery programs is followed by a scoring based on Table 1 metrics and the scores are then plotted in a radar graph and discussed in the penultimate section.

## 3. System Architecture - Connectivity and Distribution

Connectivity is defined as the manner by which and extent to which resources, species or social actors disperse, migrate or interact across ecological and social landscapes (Biggs, et al., 2012). Collaboration is actualized institutionally through the degree of connectivity of all relevant stakeholders and their capacity to participate in governance processes (Bouckaert et al., 2018). Wantzen et al (2016) proposed a notion of river culture which recognizes the intersection of hydrologic, biological and cultural uses and values of the river as a basis for preserving ecological and cultural diversity along rivers, much of which is tied to seasonal pulses in flow. The scale of the river strongly influences the river's social role (Kondolf & Pinto, 2017). In this context, the collaborative initiatives developed to balance water development with ecological concerns embodies a social connectivity around the use of the Colorado River.

Connectivity, in a biophysical sense, is the degree to which components of a watershed are joined and interact by transport mechanisms that function across multiple spatial and temporal scales and is determined by the characteristics of both the physical landscape and the biota of the specific system (Alexander, et al., 2018). This definition reflects a systems perspective of watersheds as heterogeneous mosaics of interacting ecosystems in which variations in the duration, magnitude, frequency, timing and stability of flows form dynamic, spatiotemporal continua of connectivity (Alexander, et al., 2018).

### 3.1 Social/Institutional Indicator: Collaboration

The Upper Colorado River Endangered Fish Recovery Program (UCR-EFRP) was established in 1987 after 3 years of discussion, data analysis and negotiations by representatives of the US Fish and Wildlife Service (USFWS), Bureau of Reclamation, the states of Colorado, Utah and Wyoming; and environmental and water development interests. Three species, the Colorado squawfish, humpback chub and bonytail chub had been listed as endangered by the Secretary of the Interior under the Endangered Species Act (ESA) of 1973. A fourth species, the razorback sucker, was a candidate for Federal listing under the ESA. The recovery program was developed as part of a cooperative effort involving multiple agencies and organizations that had an interest in how the Upper Colorado River Basin and its resource are managed. The Upper Basin States have a development interest in the river's resources, while Reclamation operates a number of Federal reservoirs of a range of sizes from large to small. The USFWS is responsible for administering the ESA. Water resource organizations too have a development interest that balances States' water rights systems, interstate compacts and fish recovery goals. A number of national and Statewide conservation organizations are interested in realistic and effective fish recovery and habitat preservation (USDOI, 1987).

The April 2005 Record of Decision for the Lower Colorado River Multi-Species Conservation Program (LCR-MSCP) created the equivalent program for the Lower Basin with a similar institutional structure where Reclamation and USFWS are designated to act on behalf of the Secretary of the Interior to ensure compliance with the ESA, National Environmental Policy Act (NEPA) of 1969 and state environmental regulations for the three lower basin states of California, Nevada and Arizona. The program is a cooperative effort between Federal and non-federal entities, over a 50-year period, for the purpose of conserving habitat and working toward recovery of threatened and endangered species;

accommodating present water diversions and power production and optimizing opportunities for future water and power development; and providing the basis for incidental take authorizations. Other prominent Federal agencies include the Bureau of Indian Affairs (BIA), National Park Service (NPS), Bureau of Land Management (BLM), Western Area Power Administration (WAPA) and the Service. Covered actions and activities for participants occur in La Paz, Mohave and Yuma counties in Arizona; Imperial, Riverside and San Bernadino counties in California; and Clark County in Nevada (USDOI, 2005).

### 3.2 Biophysical Indicator: Water Flows

The upper Colorado River and its principal upper basin tributary – the Gunnison River – have their headwaters in the Rocky Mountains in central Colorado. The Yampa River and White River, major tributaries of the Green River, likewise have their sources in the Rocky Mountains. The annual hydrographs of these rivers are dominated by snowmelt runoff, which usually begins in late April, reaches a peak in May or early June, and recedes through July. Summer thunderstorms are common and can cause localized flooding on tributaries and increase turbidity on the larger rivers for days, but do not have a significant effect on main stem discharges (Van Steeter & Pitlick, 1998).

Natural streamflows of the Colorado and Gunnison Rivers are affected by many diversions and dams. Collectively, the reservoirs upstream of the Flaming Gorge and Glen Canyon dams store only about 10% of the total volume of water in Lake Powell. However, these reservoirs are near the source of the runoff and thus alter the annual hydrograph significantly. Composite records indicate that in the post-development period (1950 – 1995), annual peak discharges of the Colorado River at Glenwood Springs have averaged 286 $m^3/s$, which represents a 43% decrease relative to the pre-development period (1900 – 1949) average of 504 $m^3/s$. The effects of reservoirs and transbasin diversions in the upper Colorado River basin diminish downstream because of added flow from unregulated tributaries (Van Steeter & Pitlick, 1998).

Since the Glen Canyon dam first began to store water in 1963, creating Lake Powell, some 430 km (270 miles) of the Colorado River, including the Grand Canyon National Park, have been virtually bereft of seasonal floods. Before 1963, melting snow in the upper basin produced an average peak discharge exceeding 2400 $m^3/s$. After the dam was constructed, releases were maintained at less than 500 $m^3/s$. The dam has also trapped more than 95% of the sediment moving down the Colorado River in Lake Powell (Poff, et al., 1997). The resultant changes in flow regime and withholding of sediment have induced drastic changes in the downstream Colorado River.

Flows of the lower Colorado River historically displayed a tremendous annual variability. Prior to major flow regulation imposed by construction of the Hoover Dam in 1936, instantaneous peak discharges as high as 8500 $m^3/s$ and as low as 0 $m^3/s$ were recorded below Yuma, AZ (Sykes, 1937). Pre-regulation photographs of the Colorado River on its delta and historical accounts depict a highly sinuous channel with a broad flood plain harboring a diverse assemblage of lotic and lentic habitats, with fine sand and silt dominating sediments (Sykes, 1937). The most notable flood events in the lower Colorado river occurred in the mid-1980s and the early and late 1990s (Tiegs & Pohl, 2005). These floods rehabilitated much of the riparian vegetation in the delta that was lost as a consequence of flow regulation. The flood regime of the contemporary Colorado River at its delta is event-based, and floods are often associated with the El Niño phenomenon (Glenn, et al., 1996). Observations based on these events culminated in the implementation of Minute 319 in 2014, which released 130 million $m^3$ of water in a pulse flow from Lake Mead to rejuvenate riparian ecosystems and supporting species in the delta region (Flessa, et al., 2013).

**Table 3. 2:** Connectivity and Distribution Scores for the Recovery Programs.

| Connectivity & Distribution | Scores for | |
|---|---|---|
| | UCREFRP | LCR-MSCP |
| **Social/Institutional** | 5 - Formalized institutional mission with excellent connectivity (USDOI, 1987). | 4 - Connectivity is good and there is shared vision and resources. However, formalization of mission has not been completely accepted by all parties (Arizona Department of Water Resources v. Mohave County, 2015) |
| **Biophysical** | 3 – Moderate to high levels of grey infrastructure on mainstem & tributaries but program mission has invested extensively on building fish passages and connectivity infrastructure (Andersen, et al., 2007). | 1 – There are numerous large dams on the Lower Colorado River mainstem making investments and actions around fish passages and connectivity infeasible. Natural habitat is in isolated pockets and backwaters (Paukert, et al., 2011). |

## 4. System Architecture - Assemblage of Elements

The sustainable management of freshwater resources requires a shift from conventional hierarchical models of water governance focusing on regulatory controls, to hybrid governance models in which collaborative, market-based and regulatory elements all play a role. The structuring of stakeholders' different value positions influences the kinds of decisions that are made on various governance issues and is important in how a wide range of decision problems can be framed in terms of choices between alternative options and the development, adaptation and refinement of such options (Lennox, et al., 2011). Stakeholder participation is essential for system design (Ackoff, 1974) and there are three levels at which stakeholder analysis could be conducted – rational level (who are the stakeholders and what are their perceived stakes), process level (how the organization manages stakeholder relationships) and transactional level (the set of transactions or bargains among the organization and stakeholders) (Elias & Cavana, 2000).

Ecological indicators can be used to assess the condition of the environment, to provide an early warning signal of changes in the environment or to diagnose the cause of an environmental problem. The use of ecological indicators relies on the assumption that the presence or absence of, and fluctuations in, these indicators reflect changes taking place at various levels in an ecological hierarchy (Dale & Beyeler, 2001). Among the range of hypotheses that summarize possible general responses of ecosystem processes to reductions in species richness, there is considerable variation in what is the minimal diversity needed for proper ecosystem functioning, which species make significant contributions and what is the effect of changes in diversity on ecosystem function (Lawton, 1994). Indicator selection is scale dependent and for the purposes of this study, defining indicators at the ecosystem level include species abundance, richness, evenness, diversity and distributions among others as compositional elements in the ecosystem (Dale & Beyeler, 2001).

### 4.1 Social/Institutional Indicator: Structuring

Both the UCR-EFRP and the LCR-MSCP fall under the broad purview of the Secretary of the Interior. The Implementation Committee (IC) of the UCR-EFRP was created in 1987 and charged with overseeing the development and implementation of specific recommendations for each of the recovery elements. The committee is comprised of representatives from Federal agencies, the three Upper Basin states, water development interests and conservation organizations. The Secretary's ultimate responsibility is in administering the ESA without impeding States' abilities to manage and administer their water and wildlife resources. This committee has more responsibility with management than recovery teams which are generally biological and research-oriented groups. The IC provides an oversight forum for major participants, the Secretarial Observer is the liaison between the Secretary and the Implementation Committee, the Program Director provides staff assistance to the Service and IC and the management and technical groups provide assistance to the IC (USDOI, 1987).

The Secretary is authorized to manage and implement the LCR-MSCP in agreement with the Lower Basin States for providing for the use of water for habitat creation and maintenance in compliance with the ESA. Given their legal entitlements to the Colorado River water and hydropower resources, the three Lower Basin States, Indian Tribes, and other non-federal interests have a vested interest in the outcome of any consultations between USBR and USFWS. The LCR-MSCP is governed by the 35-seat Steering Committee (SC), which comprises five members – the USDOI (DOI, USBR, USFWS, NPS, BLM, BIA), the Lower Basin States Water Resources Departments, agricultural and drainage districts, urban interests, power interests, and wildlife, game and fish departments. The SC appointed a working group to oversee the technical development of the MSCP with SC oversight. The work group has a number of technical subcommittees including the Biology, Hydrologic Modeling, Peer Review, Projects list, Funding and Financing, Implementation Issues, Compliance and Public Outreach Subcommittees (White, 2021).

## 4.2 Biophysical Indicator: Species Diversity (Aquatic & Riparian)

The Colorado River mainstem fish community historically comprised 10 freshwater species, of which 7 are currently federally listed as endangered and one is of special concern. Of these, Colorado pikeminnow (*Ptychocheilus lucius*), bonytail (*Gila elegans*), and razorback sucker (*Xyrauchen texanus*) were widely distributed throughout the mainstem of the river and have been the subject of various management actions for over 3 decades (Mueller, 2005). European settlement brought dramatic biological and physical change through the introduction of the channel catfish (*Ictalurus punctatus*), carp (*Cyprinus carpio*), largemouth bass (*Micropterus salmoides*), bluegill (*Lepomis macrochirus*) and several other species (Dill, 1944). Hoover dam construction in 1935 greatly altered the physical conditions which benefitted invasive species. The reservoirs and their tailwaters were stocked with recreational species and after World War II an estimated > 80 fish species, the majority of which were aggressive predators, were stocked (Mueller & Marsh, 2002).

A study (Martinez, et al., 1994) investigated the effects of the completion of Taylor Draw Dam in 1984 on the White River – the last significant free flowing tributary in the upper Colorado River – that formed Kenney Reservoir. Fishes were sampled above and below the dam axis prior to closure of the dam and in the reservoir and river downstream following impoundment. The study found that while the immediate effects of the dam to ichthyofauna included blockage of upstream migration to 80 km of documented range for the endangered Colorado pikeminnow, the reservoir also proved to have profound delayed effects on the river's species composition. Pre-impoundment investigations in 1983-84 showed strong domination by native species above, within, and below the reservoir basin. By 1989-90, non-native species comprised roughly 90% of the fishes collected in the reservoir and 80% of the fishes collected in the river below the dam. The key take-away from the study was that smaller-scale, main-stem impoundments that do not radically alter hydrologic or thermal regimes can still have profound influence on native ichthyofauna by facilitating establishment and proliferation of nonnative species.

Native fish in the lower mainstem of the river had become rare by the mid-1930s due to a combination of predation and habitat destruction (Dill, 1944). Numbers of razorback sucker and to a lesser extent bonytail rebounded when Lakes Mead, Roosevelt and Mohave formed (Minckley, 1983). Colorado pikeminnow were extirpated from the lower basin by 1975 but small populations persist in the upper basin. Bonytail and razorback sucker have experienced recruitment failure for nearly 4 decades. Wild bonytail are believed gone, with the last one captured from Lake Mohave during the late 1990s. Estimates of wild razorback sucker dropped to < 1000 individuals – approximately 100 in the Green River, 300 in Lake Mead, and 500 in Lake Mohave. The USFWS attempted a stocking of > 12 million razorback sucker fry from 1981 – 1991 in an attempt to reestablish the species in Arizona and avoid federal listing (Johnson, 1981). However, survival was extremely poor as < 200 of these fish were ever captured (Minckley, et al., 1991). It was found that following initial releases, razorback suckers were lost to resident catfish within a matter of hours (Marsh & Brooks, 1989). This led to the growing realization that predator and invasive species control needed to be adopted as a basin-wide strategy.

Tamarisk (salt cedar) is a shrub that was introduced into the American Southwest in the late 1800s and has spread throughout the Colorado plateau by occupying islands, sand bars and beaches along streams. Historical photographs show tamarisk spread from the northern Arizona to the upper reaches of the Colorado and Green Rivers at a rate of about 20 km/yr (Graf, 1978). Tamarisk has a reputation for having negative impacts on riparian ecosystem structure and processes, including high water use compared to native plants (Taghvaelan, et al., 2014), increased soil salinization (Ohrtman, et al., 2012), displacement of native vegetation (Glenn & Nagler, 2005), changing erosion and sedimentation regimes (Vincent, et al., 2009), increased fire frequency (Busch & Smith, 1993), reduced biodiversity (Harns & Hiebert, 2006) and reduced habitat quality for wildlife (Bailey, et al., 2001) (Hinojosa-Huerta, et al., 2013). Zavaleta (2000) reported that the negative effects of tamarisk water consumption on agricultural and municipal water supplies, hydropower generation and flood control reach an annual value of US$285 million.

Tamarisk control attempts have had varied success, with control strategies such as mechanical removal, fire and herbicide treatments, though these have proved costly and with negative impacts on the native plant and soil communities (Hultine, et al., 2010). A biological control program led to the selection and approval of two insects in 1994 – the saltcedar leaf beetle from central Asia and a Middle-Eastern mealy bug for tamarisk control. In 1999, populations of tamarisk beetles were imported into the United States (Dudley & Deloach, 2004). However, in the early 1990s it was determined that the endangered southwestern willow flycatcher (SWWF) was nesting in tamarisk habitat and showed a distinct preference for disturbed habitat (Hultine, et al., 2010). Given its current preference for tamarisk habitat, replacement of tamarisk by native vegetation may negatively impact SWWF conservation efforts. Furthermore, the rate of defloration of tamarisk has far exceeded the rate at which native vegetation is regenerating (Dudley & Bean, 2012) and this has resulted in large areas showing lower total foliar cover, which has implications for vital ecosystems processes such as nutrient cycling (Hultine, et al., 2010).

**Table 3. 3:** Assemblage of Element Scores for the Recovery Programs.

| Assemblage of Elements | Scores for | |
|---|---|---|
| | UCREFRP | LCR-MSCP |
| **Social/Institutional** | 5 – Polycentric structure with different levels of decision-making with Implementation Committee overseeing broad | 3 – Steering Committee oversees broad program policy and implementation with some technical committees carrying |

| | | |
|---|---|---|
| | policy, Management Committee overseeing program management and other technical committees carrying out actions. Considerable personnel and functional redundancy across levels of decision-making (USDOI, 1987). | out actions on the ground. Horizontal structure with some redundancy but functionally diverse stakeholder aggregation (USDOI, 2005). |
| **Biophysical** | 3 – A combination of heavily developed and relatively free-flowing rivers has created a two-state system with invasive stocking in reservoirs for recreational fishing and heavy management for endangered native species propagation downstream to conserve biodiversity (Carlson & Carlson, 1982). | 2 – Most reservoirs have invasive species. Native species are stocked in specially created backwater ponds and refugia after being reared in hatcheries. Low species diversity (Ohmart, et al., 1988). |

## 5. System Dynamics – Social and Natural Capital

Collective action can often involve leaders, who have a larger role than other group members in the establishment of goals, logistics of coordination, monitoring of effort, dispute resolution and so on. Leadership is multi-dimensional and can vary from passive influence versus active motivation of group members; distributed across multiple individuals (polycentric) versus concentrated in a single individual; based on persuasive reasoning versus coercion; situational versus institutional; and achieved due to past actions or ascribed based on kinship or social identity (Glowacki & von Rueden, 2015). How power distribution occurs when leadership is concentrated is based on an individual's social value orientation, defined as a relatively stable preference for how valuable outcomes are distributed between oneself and others (Harrell & Simpson, 2016). Social value orientations can range from *individualists* seeking to maximize their own outcomes with little regard for the outcomes of others; *competitors* who seek to maximize the difference between own and others' outcomes and *prosocials* who tend to maximize joint outcomes and to minimize differences between own and others' outcomes (Van Lange, et al., 1997).

There are several compelling reasons to consider material/nutrient cycling in streams. Firstly, to the extent that nutrients are limiting in streams, they regulate rates at which important ecological processes take place such as primary productivity or decomposition. Changes in these result in alterations of stream community structure. Secondly, elemental dynamics in streams link aquatic and terrestrial/riparian ecosystems and instream processes are sensitive to watershed alterations (Meyer, et al., 1988). Thirdly, within-stream processes can alter the timing, magnitude and form of elemental fluxes to downstream ecosystems and alter downstream community structures. Fourth, dissolved organic carbon (DOC) dynamics have an important role to play in stream energy budgets. Fifth, many anthropogenic assaults on streams have been nutrient additions leading to major alterations of stream communities (Meyer, et al., 1988). Furthermore, the intermixing of surface and groundwaters occurs at different spatial scales connected by two possible vectors that may either be groundwater flow from the uplands through riparian zones to the active channel or surface water recharging groundwater along an upstream-downstream gradient (Dahm, et al., 1998).

## 5.1 Social/Institutional Indicator: Leadership

The Implementation Committee of the UCR EFRP consists of representatives of major participants including the Regional Director for Region 6 of the USFWS, the Regional Director of the Upper Colorado Region from USBR and representatives (one each) appointed by the Governors of Colorado, Utah and Wyoming. The Area Manager of WAPA is also a member because of its relationship with Reclamation and program revenues. Additionally, founding documents recommended a representative of water development interests and a representative of conservation organizations to be included. The IC selects its own chairperson and also includes two non-voting members – the first appointed by the Secretary as an observer to provide a direct liaison between the IC and the Secretary; and the second, a Program Director, appointed by the USFWS Regional Director, to serve as a staff person (USDOI, 1987). Initial funding costs were split between Federal and state governments, with USBR bearing the lion's share of costs followed by the USFWS. Annual base funding to date has been provided from Colorado River Storage Project hydropower revenues (UCR-EFRP, 2020)

A Memorandum of Understanding (MOU) signed in 1995 among the three lower basin States (including wildlife resource agencies) and the DOI led to a Memorandum of Clarification (MOC) on July 1996 for the development of a MSCP for the lower basin. The USBR and USFWS are co-leads for ensuring compliance with the National Environment Policy Act (NEPA) of 1969. The LCR MSCP permit applicants have applied to the Service for an incidental take permit, pursuant to section 10(a) of the ESA. The total cost of the Program is estimated at $626,180,000 (in 2003 dollars) over the 50-year period, with 50% of the costs borne by the permit applicants and 50% borne by the US government. The Steering Committee meets at least once a year to work on Program implementation, work plan and budget. The Program Manager is under the supervision of the Regional Director for Reclamation's Lower Colorado Region (USDOI, 2005).

## 5.2 Biophysical Indicator: Material Cycling

Floodplain nutrient cycling is often measured by utilizing leaf litter production and decomposition. Although floodplain nutrient cycling is relatively well understood in mesic regions, decomposition patterns on dryland floodplains are complex and not well-studied. Before the construction of Hoover and Glen Canyon dams in 1935 and 1964 respectively, discharges to the delta reached an estimated 6000 $m^3/s$ and the delta occupied 780,000 ha (Glenn, et al., 1996). Post-dam construction, practically no water flowed into the Gulf of California, and sediment supply to the basin has been held up in the upstream reservoirs. High precipitation-induced water releases in the early 1980s and early and late 1990s allowed sufficient water to reach the delta, but the water was polluted due to agricultural and municipal water returns (Glenn, et al., 2001). High concentrations of selenium and organochlorine pesticides have been observed in the biota of the estuary, exceeding the toxic threshold in 23 and 30%, respectively (Garcia-Hernandez, et al., 2001). Part of the estuarine basin if the Colorado River is now regarded as the agricultural “sewer” of the Wellton-Mohawk irrigational system of Imperial Valley (Carriquiry, et al., 2011).

Miller (2012) studied longitudinal patterns in DOC loads and chemical quality in the Colorado River from the headwaters in the Rocky Mountains to the US – Mexico border from 1994-2011. The findings of the study reveal that a shift from the historically snowmelt driven Colorado River to a heavily regulated system dominated by storage levels in Lake Powell has coincided with a shift from a net increase to a net decrease in DOC loads. This hydrologic shift has also resulted in a geopolitical shift in defining the Colorado river reaches 1 through 5 as being the upper basin and reaches 5 through 10 as being in the lower basin. The study revealed that net DOC input in the upper basin was greater than the net loss, while the reverse was true for the lower basin. The average annual discharge and DOC loads in the upper basin increased from reach 1-5 by $6.6 \times 10^9$ $m^3/yr$ and $2.7 \times 10^7$ kg/yr respectively. Increase in dam storage in the lower basin resulted in average basin-scale loss of $4.4 \times 10^9$ $m^3/yr$ of water, in part, to evaporation and a corresponding decrease in average DOC load to $2.2 \times 10^7$ kg/yr.

No reliable data is available for nutrient fluxes in the Colorado River across the international border prior to dam construction. However, nitrogen cycling and phosphate precipitation in US reservoirs resulted in removal of nutrients (Daessle, et al., 2017). Despite this, the upper Gulf of California is still considered as an important area for marine primary productivity, with peak chlorophyll-*a* concentrations of 18.2 mg/m$^3$ (Millan-Nunez, et al., 1999). The upper Gulf of California hosts important fisheries of shrimp, shark and sea bass (Galindo-Bect, et al., 2000) and the rich coastal productivity is assumed to remain sustained by the addition of nutrients via sediment re-suspension and surface-groundwater input from agricultural runoff drains associated wetlands, recycling of nutrients in the water column and/or input from the Gulf of California (Millan-Nunez, et al., 1999). In the Mexicali Valley, fresh surface water is limited to irrigation and drainage channels. A few wetlands are supported by drainage and wastewater flows, including the Cienega de Santa Clara. However, the main riverbed remains mostly dry in its course along the estuary (Daessle, et al., 2017).

**Table 3. 4:** Social and Natural Capital Flow Scores for the Recovery Programs.

| Capital Flows | Scores for | |
|---|---|---|
| | **UCREFRP** | **LCR-MSCP** |
| **Social/Institutional** | 3 – Federal agencies cooperate with State agencies to resolve water resource issues in concert with conservation concerns. Federal agencies must consult with Fish and Wildlife Service and State wildlife agencies (UCR-EFRP, 1988). | 2 – There is extensive detailing of which Covered Actions are discretionary and which non-discretionary and how to deal with the legal uncertainties regarding these, as well as quantification of the effects of covered actions with considerable reliance on judicial mediation pathways in cases of conflicting priorities (LCR-MSCP, 2005). |
| **Biophysical** | 3 – Considerable heterogeneity in water chemistry profiles consistent with Serial Discontinuity Concept (SDC) indicating abrupt changes due to infrastructure (Hensley, et al., 2020) and an amelioration of conditions with distance downstream through contributions of free-flowing tributaries (Stanford & Ward, 2001). | 2 – Tributaries increase the relative importance of terrestrial organic matter through addition of pulsed flows and this process increases in importance in heavily dam regulated segments (Sabo, et al., 2017). However, recovery is heavily challenged by high levels of flow regulation (Stanford & Ward, 2001). |

## 6. System Dynamics – Renewal and Continuation

A learning organization is defined as "an organization that is continually expanding its capacity to create its future" (Senge, 1990); in other words, an organization that is striving for excellence through continual renewal (Witt, 1995). Learning at different scales manifests differently with examination of operational paradigms at system level, strategic planning exercises at organizational and program levels and changes in behavior, attitudes, relationships and activities at individual levels (Watts, et al., 2007). Lant, Milliken & Batra (1992) offer a more complex explanation of organizational learning by stating that "renewal hinges not so much on noticing new conditions, but on being able to link environmental change to corporate strategy and to modify that linkage over time". Furthermore, another shortcoming is the failure to address the fundamental tension of strategic renewal – the tension between exploration and exploitation (Crossan & Berdrow, 2003). Organizational learning theory does not address new competency development while concurrently exploiting existing ones (Watts, et al., 2007).

Fisheries management and conservation biology have similar agendas as both seek the long-term viability of fish stocks albeit for different reasons. Conservationists are interested in maintaining biodiversity while fisheries managers are interested in maximizing productivity. Conservation biology has long emphasized the importance of practices such as environmental enrichment, pre-release training programs and soft release to improve post-release survivorship of captive-bred animals. In contrast, the production of ecologically viable individuals is not part of the hatchery equation because the production of large quantities of fish, rather than natural history, behavior and ecology, largely guides hatchery practices. The level of success and funding of hatchery programs is often determined by the number of fish released rather than by survival rates of those fish (Brown & Day, 2002).

## 6.1 Social/Institutional Indicator: Learning

The Department of the Interior has clear cut procedures and documentation for the implementation of adaptive management in river restoration programs. Both the UCR-EFRP and the LCR-MSCP incorporate adaptive management in program activities and decisions. The basis for the programs rested on a Biological Opinion issued by the USFWS and a Habitat Management Plan was accordingly drawn. This has been revised perennially based on available scientific research and monitoring efforts. The programs incorporate a "trial and error" approach and constantly improve and innovate based on changing conditions.

The UCR-EFRP program considered two alternatives for in-depth evaluation, including a "No Action" alternative that would involve continued Section 7 consultations with basic and applied research and monitoring, over an initial 15-year period and a "Proposed Action" alternative which involved habitat management, development and maintenance; rare fish stocking, non-native fish management and sportfishing; and research, monitoring and data management (USFWS, 1987). The program has come up for extended authorization twice since 1987 and is undergoing a reevaluation of conservation priorities following a recent decision to down-list two species that have achieved sufficient levels and aim for continued, long-term management.

The LCR-MSCP program was conceptualized as a 50-year program in 2005 and has so far not undergone significant reframing of program policies and procedures. The SC commissioned two separate scientific reviews of interim conservation strategy documents during program development in 1999 and 2002. The first review was conducted by the American Institute of Biological Sciences and the second Science Review Team comprised 6 members selected from a list of 18 active interdisciplinary scientists with a working knowledge of Southwest ecosystems. Out of three action alternatives considered, including a "No Action" alternative, a combination of two other plans was selected as the preferred alternative on the basis of it realizing the full range of environmental goals to effectively conserve species while allowing water use under existing entitlements. This alternative has been the basis of yearly plans and progress to date.

### 6.2 Biophysical Indicator: Species Recruitment

The sheer amount of grey infrastructure in the mainstem of the Colorado river has created insurmountable barriers for migratory fish such as Colorado pikeminnow to migrate upstream and spawn. The Hoover and Glen Canyon dams have cut off the possibility of integrated management of upper and lower basin species. The Upper Basin offers more opportunities for species recruitment because of the presence of unregulated tributaries that serve as refugia for endangered native fish species. The Lower Basin has seen the sharpest declines and near extermination of the Colorado pikeminnow as well as razorback sucker and bonytail, both of which saw some resurgence with the creation of lower basin lakes and reservoirs.

The current restoration strategy is to limit and prevent movement of invasive game fishes out of impoundments and curtailing future stocking by enacting public education programs. Increasing the harvest of carp and channel catfish are also promoted. Because of the recreational values put on sport fishing, these measures of non-native fish control have faced challenges in implementation. Nonnative sport fishes continue to proliferate by reproducing in river channels and invading from off-channel habitat (Tyus & Saunders III, 2000). Additionally, small, nongame fishes such as the red shiner and fathead minnow that were unintentionally introduced, have proven to be aggressive, abundant and widely distributed, constituting over 90% of the standing crop of fishes in backwater habitat used as nursery areas by the listed fishes (McAda, et al., 1994).

Two resource philosophies evolved in the Colorado River basin in the late 1980s: (1) the establishment of the Upper Colorado River Basin Recovery Implementation Plan in 1987; and (2) a conservation movement to actively manage two endangered species in the lower basin, which began in 1989 (Mueller, 1995) and later became the LCR-MSCP. In the upper basin, a consortium of resource agencies and water users came together to establish a recovery regime that would occur in 15 years in conjunction with continued water development. Initial recovery centered on habitat restoration, including the restoration of historic flow regimes which had been disrupted by reservoir storage. Since 1990, emphasis shifted toward restoring floodplain wetlands and predator removal and control (Lentsch, et al., 1996) (Wydoski & Wick, 1998).

Both razorback sucker and bonytail established impressive communities when several reservoirs filled in the lower basin, with the razorback population in Lake Mohave swelling to > 100,000, while bonytail were less numerous. This was before the introduction of nonnative species. Bonytail became extremely rare by the early 1980s. Stocking of bonytail in Lake Mohave began in 1980 (Minckley & Thorson, 2004) and a similar stocking effort for the razorback sucker began in 1989 (Mueller, 1995). The approach involved capturing wild larvae and rearing them to a size large enough to avoid predation. The goal was to capture genetic variability that would have been lost in hatchery production (Mueller, 2005). Due to the short supply of hatchery rearing space, fish were reared in municipal ponds, isolated reservoir coves and backwaters blocked by nets (Mueller, 1995). The concept expanded to other reaches of the lower river under the LCR-MSCP.

**Table 3. 5:** Renewal and Continuation Scores for the Recovery Programs.

| Renewal and Continuation | Scores for | |
|---|---|---|
| | **UCREFRP** | **LCR-MSCP** |
| **Social/Institutional** | 3 – The program has conducted 5-yearly Species Status Assessments to monitor endangered fish populations and has recommended two species for delisting based on these (Elverud, et al., 2020). Cooperative agreements for extension of program and funding have been implemented in 2001 and 2009 and will be renewed again in 2023. | 3 – Adaptive management occurs at project and program levels with review of reports and monitoring results at project level and adjustments to Habitat Conservation Plans (HCPs) requiring adjustments to funding levels, revisions to HCP conservation measures and adoption of alternative conservations measures (LCR-MSCP, 2020). |
| **Biophysical** | 3 – Favorable thermal gradients in tributary habitats such as the Green and White Rivers spur seasonal migrations to spawning locations, however declines in mainstem river populations remain due to habitat alterations (Fraser, et al., 2017). | 2 – Apart from the Little Colorado River below the Grand Canyon which is still free-flowing and has a natural thermal flow regime, habitat degradation has extirpated most endangered species in the mainstem (Fraser, et al., 2017). |

## 7. Results and Discussion

Based on the detailed analysis of various social and biophysical indicators in the previous section, a scoring of the indicators was performed using ratings on a scale of 1-5, based on an assessment of the evidence. The scoring is undertaken for both the Upper Basin and the Lower Basin restoration programs and the scores are listed in the Table 1 below (with detailed construction information in Appendix A). The indicators are rated on a scale of 1-5, with the ratings representing a gradient or degree of variation of the particular indicator based on available literature reviews. Based on the scoring described in Appendix A, the two programs – the UCR-EFRP and the LCR-MSCP were rated for each of the indicator categories at both social and biophysical levels. Figures 2 and 3 below describe the extent of resilience achieved based on the metrics scored and informs the extent of feedbacks and potential trade-offs inherent in a SES system.

### 7.1 The UCR EFRP

Figure 2 below shows that the UCR-EFRP has performed better in terms of contributing to social / institutional resilience than biophysical resilience. The collaboration as well as system structuring of the program around the goals of habitat restoration and native species conservation is strong, though the biophysical system shows moderate amounts of connectivity owing to the presence of significant dams and reservoirs including the Flaming Gorge dam, the Aspinall Unit, the Navajo Reservoir and the Glen Canyon Dam. These have an impact on species diversity by resulting in a development of a two-state system, where recreational values have resulted in invasive species dominating reservoir systems and downstream areas being dominated by native species at risk of invasive species encroachment, thereby requiring long-term management to ensure native species preservation.

Furthermore, a number of tributaries in the Upper Basin are relatively less developed and more free-flowing and provide crucial refugia for migratory species spawning. This is a principal reason why natural capital cycling and ecosystem processes flourish better further downstream of the big reservoirs. The social capital is also strong, and because of the implementation of strong adaptive management processes the feedback between the social and biophysical elements appears to be strong. Though the initial Biological Opinion appeared to have limited options scientifically for restoration scenarios, there has been significant improvement in scientific studies over the decades since program inception and a strong public awareness campaign to recruit public support for achieving program goals through invasive species control.

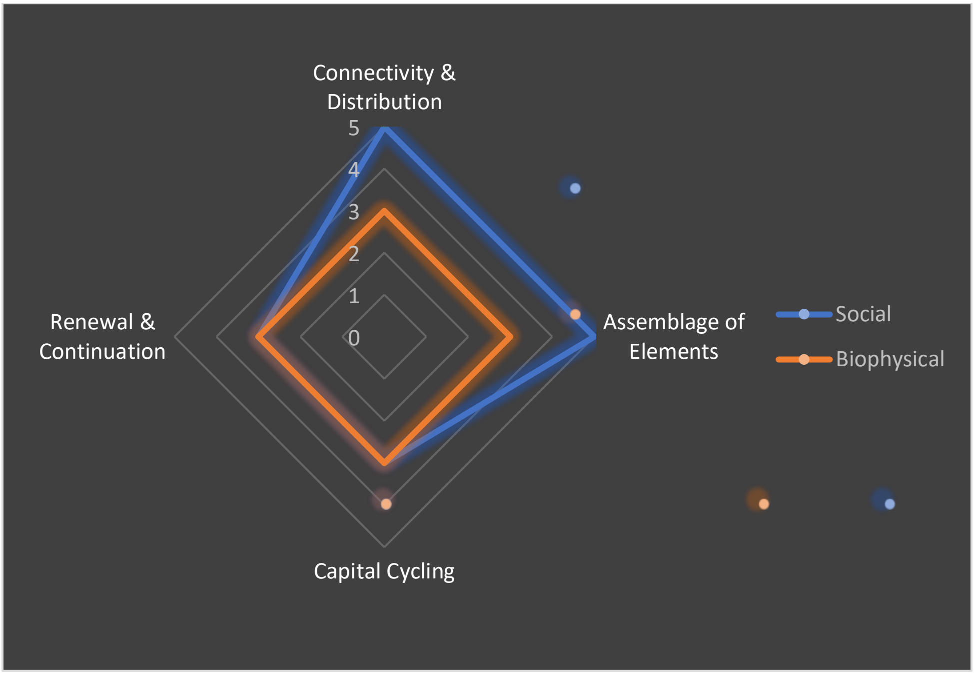


**Figure 3. 2:** SES Resilience Assessment for UCR-EFRP.

System renewal in terms of institutional learning is lower rated because the predominant paradigm of the program is mitigation rather than full-scale restoration. So, although significant financial capital has been invested in building infrastructure to facilitate migratory fish passages and stocking programs to maintain native fish populations, the overdependence on technological solutions in a highly engineered system is less conducive to incorporating actual biophysical feedbacks and responding to them. Despite the high levels of infrastructure, the system still retains some biophysical resilience because of flow control and recruitment facilitation as well as large stretches of undeveloped tributary systems.

## 7.2 The LCR-MSCP

Figure 3 shows that the LCR-MSCP is less resilient overall and shows significant systemic vulnerabilities. These are partly because of the way the program is structured and partly the context in which the program is situated. The Lower Basin mostly comprises the main stem of the river with the tributaries also being in a greater state of development as compared to the Upper Basin. The Upper and Lower Basins are divided by the insurmountable barriers of the Hoover and Glen Canyon Dams and there are large and small dams and diversions at various reaches all the way to the Mexican border. The amount of flow regulation is significant and this creates a highly disconnected system at a biophysical level. Therefore, even though the collaboration based on economic and regulatory incentives is strong though not all-inclusive, with Indian Tribe involvement being minimal to insignificant, the prevalence of a feedback between social and ecological elements is broken.

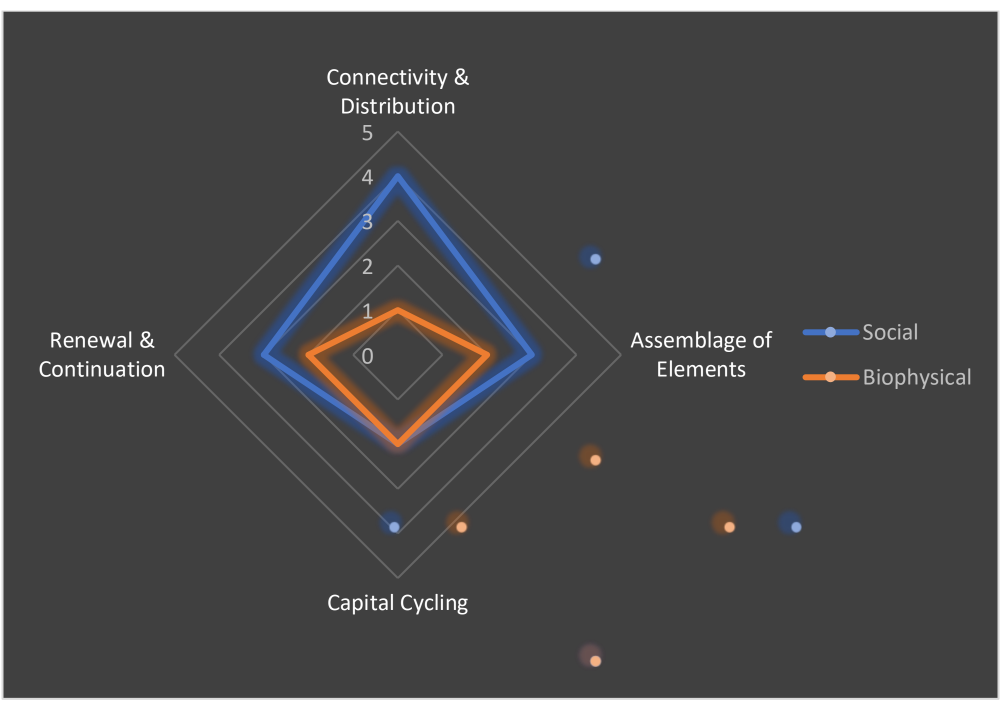


**Figure 3. 3:** SES Resilience Assessment for LCR-MSCP.

The way adaptive management is structured in the Lower Basin is geared toward establishing isolated backwaters and aquatic landscapes for native species to flourish and managing invasive species. Therefore, though species diversity may exist in these isolated pockets, they are being propped up by technological interventions such as hatchery breeding and stocking programs. Institutional structuring in the Lower basin is also heavily geared toward mitigating the impacts of take by senior water rights holders at various scales from state to local. Therefore, both social and biophysical structuring elements are a lot weaker here.

This is also the reason for social capital being more concentrated in a hierarchical structure to allow for water allocation goals to be met and this creates a significant disruption in ecosystem processes because over-allocations, pollution from overuse and impending drought have combined to create a heavily degraded system at a biophysical level. The adaptive capacity of the institutions is also more toward meeting compliance requirements, and because of the high barriers to species recruitment and the creation of a two-state system as in the Upper Basin, the capacity for the system to renew itself is heavily compromised.

## 8. Conclusion

Dams function as system disruptors and can also create geopolitical and biophysical dichotomies that take significant social momentum to change. This does not appear to be the trajectory for the Colorado River as has been the case for other river systems in the Pacific Northwest. Besides, the sheer scale of the dams, the heavy water use and consequent degradation in water quality, high invasive species prevalence and critically declining levels of native fish species has resulted in the Colorado River system being close to a tipping point. It is unclear whether there can be a significant pathway to deep river restoration, considering that economic growth in the Lower Basin states is still high and populations are expected to grow even more. The Drought Contingency Plan has addressed short term risks involved by facilitating voluntary cutbacks to water use without addressing the underlying causes of the problem.

The Law of the River has been the backbone of water rights allocations for the Colorado River and has been hailed as such. However, Manifest Destiny was expected to have ended a century ago and it shows no signs of stopping. However, the legal structure has resulted in absolutism in terms of water allocation values, in terms of gray infrastructure to achieve those water allocation values and also in terms of the mechanisms available to address systemic shortages. This level of absolutism has created a dangerous level of vulnerability for the system. At smaller sub-regional scales, trading of water leases and shifting water consumption patterns have created some flexibility to deal with impending water shortages. But the capacity of the system to provide for burgeoning demand and population growth is still seriously compromised and sub-regional scale water shuffling is akin to moving deckchairs on the Titanic. For a transformative pathway to water governance of the Colorado River in the era of climate change and impending drought, two major considerations need to be accounted for – that of incorporating greater uncertainty into the framework of the Law of the River, and that of decoupling future regional economic growth from water.

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# APPENDIX A

# EXAMPLES OF DEFINITE AND AMBIGUOUS CODES

| Code | Examples of statements | |
|---|---|---|
| | **Definite** | **Ambiguous** |
| **Supportive** | ….recommended the Management Group be directed to review the work plan to identify activities that would expedite acquisition of water rights and protection of instream flows (1989).<br><br>…..agreed to invite appropriation committees staff and Service people (1993).<br><br>…..also encouraged the Service to be sure to emphasize accomplishments as well as shortcomings in the sufficient progress letter (1998).<br><br>…..suggested that as we prioritize activities, we may want to reconsider the need for passage at Hartland (2002). | …..said that he thinks we're just now beginning to get to the question of whether all the RIPRAP actions are financially feasible (1995).<br><br>…..countered that the extension is needed because Reclamation budgets three years forward and won't have funds for needed capital project recovery activities if we don't extend the authorization (2002).<br><br>The Service anticipates completing the biological opinion later this year (2017). |
| **Clarifying** | …..pointed out that the draft biological opinion identified both water depletion and sediment issues, and that sediment impacts could have been a project sponsor responsibility were it not for the Recovery Program's recent efforts to begin addressing the sediment Issue (1989).<br><br>When asked how their funds would be contributed to Recovery Program activities (through the regular process or with certain stipulations), ….replied that when they go to Congress for funding, they have to identify what projects the funding will be used for (1992).<br><br>…..noted that water users provided a draft to the Colorado delegation in Washington last week (1997).<br><br>…..replied that with the expansion of smallmouth bass, things have really declined (2003).<br><br>…..clarified that ….was only being thorough and describing all possible approaches, not suggesting that the Program or the Service would endorse them (2010).<br><br>…..asked about the projected nonnative fish screen costs at the Ridgway Reservoir spillway (2016). | …..suggested that the cost-sharing CREDA is proposing is a good concept headed in the right direction (1994).<br><br>…..said he envisions that the Yampa Management Plan and related programmatic biological opinion would be reviewed at the Management Committee level such as was done on the 15-Mile Reach PBO (2000).<br><br>…..said he always assumed we would request extended authorization, but it's uncertain at this point what purposes power revenues might be needed in addition to O&M and monitoring (2006).<br><br>…..added we also might want to mention that we don't want to push development into other species' habitats of concern (2014). |
| **Conditional** | …..emphasized that they would not support any more-Program funding for the San Juan River unless it was incorporated into the Program (with additional funds) (1990).<br><br>…..said he supports the idea of including credits in principle, but he's concerned that the way we've approached it has increased | …..suggested that the key players in the 15-mile reach work together to define future direction, but that FY-91 studies stand (1990).<br><br>…..said they need to have some kind of affirmation from the Service that the dual goals of the Program are achievable (1996). |

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| | the Federal funding commitment by 30% (1997).<br><br>…..concluded that we've made progress in coming to agreement on technical questions, but much more is needed on management and implementation (more than just the Fish and Wildlife Service is required for that) (2003).<br><br>…..fully supported the concepts in ….memo, everyone wants to recover these fish, but he agreed with ….that we need to retain some flexibility so we don't set ourselves up for the next failure (2015). | …..suggested one alternative to this proposal would be to prioritize projects (noting that one capital project in particular has especially escalate (2005).<br><br>…..suggested a discussion of a 'roadmap to recovery' may be better suited to the Management Committee (2015). |
| **Critical** | …..expressed concern that there were inconsistencies between the draft recovery plans and provisions of the Recovery Implementation Program (1988).<br><br>…..pointed out that he had similar reservations about the July-September recommendations, which the Board adopted (1991).<br><br>…..questioned whether the Park Service brings the same strong commitment in seeing the Recovery Program succeed and the broad-based interest as other Program participants (2000).<br><br>…..noted that he disagrees with the first sentence of agenda item #11 (that the basin fund status is due to the drought) (2004).<br><br>Despite our efforts, ….believes our nonnative fish management actions are not working well enough (2013). | …..has stated that because flows in the 15-Mile Reach will be significantly affected, this may be a direct impact, as opposed to a depletion impact covered by the Recovery Program (1995).<br><br>…..said he believes the science on selenium in the PBO is not current, and thus the definition of what constitutes a threat to the fish is no longer valid (2009).<br><br>…..referenced….earlier comment that we clearly haven't gotten the nonnative fish problem under control (2013). |

# APPENDIX B

## INDICATORS AND SCORING FOR SOCIAL AND BIOPHYSICAL COMPONENTS OF THE SYSTEM

| Category | Social | Sources | Biophysical | Sources |
| --- | --- | --- | --- | --- |
| **Connectivity & Distribution** | 1 - There is no social connectivity/collaboration and a lack of shared interests or considerable conflict.<br>2 – There is little connectivity and little shared interests.<br>3 – There is some connectivity and the beginnings of convergence to a shared vision.<br>4 – There is good connectivity and the presence of a shared vision and resources.<br>5 – The connectivity is excellent and the institutional mission is formalized. | This is adapted from the degrees of connectivity between the people collaborating, activities and design elements (Gambatese & AlOmari, 2016); (AlOmari & Gambatese, 2016). They define degrees of connection (DoC) 1-4 as follows:<br>(1) Interacting with the design element during its construction.<br>(2) Interacting with the design element in its final form to attach another component to it.<br>(3) Or by working in the vicinity of it.<br>(4) And indirectly interacting with the design element through another worker.<br>The design element in this study is the shared interests & vision. Level 1 of the social component is a zero in terms of connectivity and shared interest. Levels 4-5 correspond to financial & legal investment in vision construction. | 1 – High levels of gray infrastructure and highly regulated flows over >70% of the river with very little natural habitat remaining.<br>2 – High levels of gray infrastructure and high flow regulation, isolated, fragmented habitat for native species.<br>3 – Moderate to high levels of gray infrastructure with significant flow regulation, but fish passages and effort to protect/restore habitat for native species and prevent fragmentation.<br>4 – Low levels of gray infrastructure with more natural flow regimes and variability supporting aquatic and riparian habitat. Little fragmentation.<br>5 – Mostly free-flowing river with low fragmentation and no barriers to fish passage. | The degree of connectivity influences species assemblage (Dos Santos & Thomaz, 2007). (Zilli & Paggi, 2013) describe different degrees of connectivity in relation to wetland siting and characterize them as disconnected, temporarily or permanently connected. Water flows are facilitated by the level of hydrologic connectivity and this is disrupted by human activities including dam construction. The ecological indicators incorporated differing levels of connectivity & disruption between mainstem & wetlands. |

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| **Assemblage of Elements** | 1 – Functionally distinct expertise with no overlap. Little representation of all affected parties.<br>2 – Functionally diverse expertise with little overlap. Some representation of affected parties.<br>3 – Functionally diverse expertise with redundancy. Moderate representation of affected parties.<br>4 – Significant functional diversity and redundancy and high levels of representation and accountability.<br>5 – Polycentric structure with good representation and accountability. | There are conditions at which redundancy and diversity at local levels enhance performance as long as there are also overlapping units of government that can (1) resolve conflicts, (2) aggregate knowledge across diverse units, and (3) insure that when problems occur in smaller units, a larger unit can temporarily step in if needed (Low, et al., 2003).<br><br>Diversity in team members can manifest as ***separation*** where members hold opposing positions on tasks, ***variety*** where team members bring a multiplicity of information sources to bear on an issue and ***disparity*** where one member of the team is superior to others in terms of expertise (Harrison & Klein , 2007). | 1 – Highly altered ecosystem with preponderance of invasive species and extinct / critically endangered native species. Low species diversity.<br>2 – Ecosystem having high levels of invasive species and critically endangered native species. Close to tipping point. Low species diversity.<br>3 – Ecosystem with endangered and threatened native species at a precarious state of co-existence. Moderate species diversity.<br>4 – Ecosystem with some invasive species but still retaining high species diversity and prevalence of native species.<br>5 – Relatively undisturbed system with high species diversity. | Ecosystem alterations can affect the abundance, distribution and diversity of species, and thus potentially change the relative strength of bottom-up (the plant resource) and top-down (natural enemies) trophic forces acting on populations (Moreau, et al., 2006).<br><br>Exotics can affect ecosystems by altering system-level flows, availability, or quality of nutrients, food, and physical resources (e.g. living space, water, heat or light) (Crooks, 2002).<br><br>A structural perspective considers the species, guilds and communities comprising the living elements of the ecosystem (Minns, et al., 1996). |
| **Social and Natural Capital** | 1 – Top-down distribution of power / decision-making with “individualist” mindset.<br>2 – Hierarchical structure / power distribution with “competitive” mindset.<br>3 – Top-down structure with “prosocial” mindset.<br>4 – More distributed decision-making with “competitive” mindset. | Leadership can vary along several dimensions. It can involve (i) passive influence versus active motivation of group members; or be (ii) distributed across multiple individuals versus concentrated in a single individual; (iii) based on persuasive reasoning versus coercion; (iv) situational | 1 – Highly altered/degraded system with very little nutrient cycling. Ecosystem functioning significantly disrupted.<br>2 – Highly altered system with significant disruption of ecosystem processes and limited opportunities for restoration. | Holling (1987) showed how the structural and functional elements of ecosystems are linked by cyclical changes in capital, the amounts of energy and nutrients sequestered in biomass, and the degrees of ecological complexity and connectivity. |

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| | 5 – More distributed decision-making with "prosocial" mindset. | versus institutional; and (v) achieved due to past actions or ascribed based on kinship or social identity (Glowacki & von Rueden, 2015).<br><br>Prosocial, or other-regarding, group leaders will lead for the benefit of their groups, whereas proself-(self-regarding) led groups, on the whole, will be worse off (Harrell & Simpson, 2016).<br>Pursuit of self-interest or relative advantage over others may lead people to develop an individualistic or competitive orientation rather than a prosocial orientation.<br>Prosocials expect others to be more cooperative than do individualists and competitors (Van Lange, et al., 1997). | 3 – Significantly altered system with some disruption of ecosystem processes but more options for restoration.<br>4 – Moderately altered system with some disruption of ecosystem processes but high restoration potential.<br>5 – Slightly altered system with ecosystem processes not significantly disrupted and very little need for restoration. | A functional perspective stresses the movements of materials within and through ecosystems, e.g., energy, nutrients, water, and sediment. Wetlands and submerged vegetation wax and wane; great storms redistribute substrates, nutrients, and species; and each event induces rejuvenation and reconstruction of habitats and communities.<br>(Minns, et al., 1996). |
| **Renewal & Continuation** | 1 – Reactive institution operating in hindsight and not sensitive to feedback.<br>2 – Institution adapts processes and actions based on feedback but no significant learning taking place at policy level.<br>3 – Institution adapts processes and occasionally policies based on feedback | Learning and change can occur at the level of systems, organizations, groups, teams and individuals. At the system level, operational paradigms may need to be examined and networks expanded or reconfigured. At the organizational and program levels, strategic planning exercises may be | 1 – Highly fragmented system with different regimes at different points jeopardizing species recruitment and dispersal.<br>2 – High system fragmentation and low dispersal ability. High reliance on technical solutions to prop up degraded system. | The effects of a landscape on the population genetics of species is testable by the analysis of closely related taxa (e.g., species belonging to the same genus), but with differing ecological demands and dispersal abilities. A landscape therefore might be strongly fragmented for a habitat specialist with poor |

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| | but has little adaptive capacity built.<br>4 – Institution is resilient to shocks and sensitive to feedback and incorporates double-loop learning.<br>5 – Institution is highly resilient to disruptions and operates on a triple-loop learning paradigm. | useful to explore new frontiers and to assess any revisions in strategy or tactics that may be needed to identify and correct less successful paths and to address changes in the external environment. At the individual level, managers need to be more open to learning and change (Watts, et al., 2007).<br><br>Change is conceptualized as social and societal learning that proceeds in a stepwise fashion moving from single to double to triple-loop learning. The direction of institutional change is assumed to be directed at more flexible regulations that leave room for context specific implementation (Pahl-Wostl, 2009). | 3 – Moderate system fragmentation with restricted dispersal ability. High dependence on technical fixes.<br>4 – Species recruitment is possible with technical fixes and there is little need for extreme measures such as stocking and artificial transport.<br>5 – High species recruitment and dispersal ability because of low anthropogenic system demands. | dispersal abilities and more or less continuous for a more generalist species with higher dispersal capacity. Generalist species with poor dispersal abilities as well as specialist species with high dispersal abilities might show some intermediate position (Louy, et al., 2007). |