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iSAW: Integrating Structure, Actors, and Water to study socio-hydro-ecological systems

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Key Points:

- Interdisciplinary framework for human–water system sustainability.
- Water system components include structure, actors, and water.
- Framework can be applied to any natural resource issue.

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iSAW: Integrating Structure, Actors, and Water to study socio-hydro-ecological systems

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Abstract Urbanization, climate, and ecosystem change represent major challenges for managing water resources. Although water systems are complex, a need exists for a generalized representation of these systems to identify important components and linkages to guide scientific inquiry and aid water management. We developed an integrated Structure-Actor-Water framework (iSAW) to facilitate the understanding of and transitions to sustainable water systems. Our goal was to produce an interdisciplinary framework for water resources research that could address management challenges across scales (e.g., plot to region) and domains (e.g., water supply and quality, transitioning, and urban landscapes). The framework was designed to be generalizable across all human–environment systems, yet with sufficient detail and flexibility to be customized to specific cases. iSAW includes three major components: structure (natural, built, and social), actors (individual and organizational), and water (quality and quantity). Key linkages among these components include: (1) ecological/hydrologic processes, (2) ecosystem/geomorphic feedbacks, (3) planning, design, and policy, (4) perceptions, information, and experience, (5) resource access and risk, and (6) operational water use and management. We illustrate the flexibility and utility of the iSAW framework by applying it to two research and management problems: understanding urban water supply and demand in a changing climate and expanding use of green storm water infrastructure in a semi-arid environment. The applications demonstrate that a generalized conceptual model can identify important components and linkages in complex and diverse water systems and facilitate communication about those systems among researchers from diverse disciplines.

1. Introduction

In an era of global climate change and population growth, water system managers face numerous sustainability challenges. Water systems are coupled human–natural systems, being affected by both human and natural system drivers, and thus exhibit complex systems dynamics involving feedback loops, unpredictability, and uncertainties [*Liu et al.*, 2007]. Across the western United States, climate change is shifting precipitation from winter snow to rainfall and advancing the onset of runoff earlier in the year [*Barnett et al.*, 2008; *Gillies et al.*, 2012; *Bardsley et al.*, 2013], with significant consequences for water supply quantity (e.g., decreased snowpack) and timing (e.g., runoff occurring earlier in the year [*Barnett et al.*, 2008]). At longer time scales, droughts are expected to become more frequent and more severe, while flood risk is also expected to rise due to increased storm frequency and intensity [*Karl and Knight*, 1998; *Allan and*

Soden, 2008]. Meanwhile, the American West is undergoing rapid population growth and urbanization, and new residential, commercial, and industrial uses are placing competing and changing demands on water resources [*Gober*, 2010]. Ecological disturbance regimes, such as fire and bark beetle outbreaks, may be exacerbated by a changing climate [*Melillo et al.*, 2014] and could have additional implications for the water yield and water quality from mountainous and forested ecosystems prevalent throughout the region. As a result, water resource managers must address shifting patterns of water supply and demand [*Bardsley et al.*, 2013] in addition to potential changes in the frequency and severity of disturbances such as fires, floods, and droughts.

Exacerbating these challenges, the shifting patterns in hydrologic and ecological events are plagued with inherent uncertainties and discrepancies among studies, which spur scientific debate and result in inconsistent forecasts that complicate the challenge of water management in the face of changing conditions [*Vano et al.*, 2014]. These management challenges present an emerging scientific challenge to forge an integrated, interdisciplinary understanding of coupled human–water systems. Solving this challenge requires describing the most important system components and linkages of coupled human–water systems and the critical tools that water managers can use to cope with changes and sustainably manage water systems.

Many scientific disciplines have already recognized that human, hydrologic, and ecological components of water systems must be examined with integrated approaches. Attempts to illustrate these linkages have led to a proliferation of conceptual frameworks, which focus on a variety of mechanisms through which human and environmental systems are interconnected. Integrative approaches, described with varying terminology, include human–environment systems [*Acevedo et al.*, 2008; *Bennett and McGinnis*, 2008], social-ecological systems [*Collins et al.*, 2000; *Ostrom*, 2009], ecosystem services [*Millennium Ecosystem Assessment*, 2005; *Collins et al.*, 2010], vulnerability [*Eakin and Luers*, 2006; *Adger et al.*, 2009], political ecology [*Robbins*, 2004; *Molle*, 2007], hazards and risk [*Haque*, 2000; *Berkes*, 2007], and many others. These frameworks usually identify a limited set of mechanisms through which human and environmental systems are coupled (e.g., ecosystem services [*Collins et al.*, 2010] or hazards and risks [*Eakin and Luers*, 2006]). Some frameworks have focused on land-use change as the primary linkage between humans and their environment [*Acevedo et al.*, 2008], while others focus on the role of built infrastructure [*Anderies et al.*, 2004]. Most frameworks have yet to take a broad approach that considers diverse theories and types of human–environment interactions from more than a few disciplines.

Early frameworks for understanding human–water interactions specifically represented humans as static and separate from large-scale drivers of hydrology rather than as part of a dynamic coupled system [*Srinivasan et al.*, 2012]. Subsequent best practices for water management, such as Integrated Water Resources Management, Adaptive Environmental Assessment, and Adaptive Management, recommended including different research disciplines, stakeholders, and policy makers [*Holling*, 1978; *Walters and Hilborn*, 1978; *Global Water Partnership*, 2000]. However, advocates of these frameworks have also suggested major changes to governance (Integrated Water Resources Management) or management processes (Adaptive Management) without rigorously evaluating the relationships between management strategies and water outcomes [*Biswas*, 2004; *Medema et al.*, 2008]. In fact, the principles proposed in these frameworks are themselves hypotheses that need testing. Other researchers have highlighted the need for theories and research on the relationships among water management and social, environmental, and water resource outcomes [*Biswas*, 2004; *Medema et al.*, 2008].

The emerging literature on sociohydrology [*Wagener et al.*, 2010; *Pataki et al.*, 2011b; *Sivapalan et al.*, 2012, 2014] aims for a broader scope than management framework approaches, moving beyond static interactions between water and human systems to understand the co-evolutionary dynamics and emergent properties of coupled human–water systems. While the sociohydrology literature has defined a new domain of inquiry and an overarching theoretical framework for understanding coupled human–water systems, the literature to date has focused on explaining observed dynamics and has made more limited progress in setting forth concrete hypotheses to test predictions about current and future water sustainability challenges. One key exception is *Elshafei et al.* [2014], who developed a prototype conceptual framework for agricultural systems that describes the human system component at a lumped scale with aggregate indicators. However, we still need a framework that considers heterogeneous actors and their behaviors and that clearly links behavioral responses with endogenous physical and social structures. The framework should identify or hypothesize the key mechanisms linking these various actors to other water system components and enable monitoring of the effects of those linkages over time.

The diversity of approaches to study human–water systems also highlights the need for a conceptual framework that explicitly links human, hydrologic, and ecological aspects of water systems and can be applied to a wide range of water resource issues. The overarching goal of our work was to facilitate an *understanding of* and *transitions to* sustainable water systems in a world driven by major climate, demographic, and land-use changes. We did this by developing an integrated Structure-Actor-Water framework (iSAW) and applying this framework to two case study examples in urbanizing Utah. This framework was designed to be generalizable across all human–water systems, yet with sufficient detail and flexibility to be customized to specific cases.

In this study, we: (1) produced an interdisciplinary framework for water resources research and management that is flexible and capable of focusing on water issues across scales (e.g., city to region) and domains (e.g., water quantity and quality, transitioning, and urban landscapes); (2) found common ground and facilitated collaborations by providing a nexus for building a shared understanding of the complex water system in which we are collaboratively conducting research; and (3) identified key components and linkages within human–water systems to identify and address knowledge gaps and guide collaborative research designs.

2. Framework Development

2.1. Study System

This framework was developed as part of the Utah statewide iUTAH project (innovative Urban Transitions and Aridregion Hydro-sustainability), an interdisciplinary collaboration in water sustainability research, education, and outreach across academic disciplines and university institutions in Utah. The project is focused on the rapidly urbanizing area along the Wasatch Range (Figure 1), where, as of 2010, 2.4 million people (86% of Utah's population) reside and where population is expected to reach nearly 5 million by 2060 (Utah Governor's Office of Planning and Budget, http://gomb.utah.gov/budget-policy/demographic-economic-analysis). Annual precipitation in Utah ranges widely, from arid desert conditions to montane forests with abundant snowfall. Human settlements in this region have historically been supported by snowmelt from montane watersheds. Water management in the state has historically been and currently is driven by water availability, regional water compacts, and prior appropriation water law where agricultural users generally hold the most senior rights. Rapid population growth in combination with possible changes in water supply due to climate change has uncertain consequences for the future of water resource management in this region.

In response to these challenges, the iUTAH project was designed to address three key sets of research questions: (1) What is the current water balance of the region, and how vulnerable are water resources to changing climate and urbanization? (2) What is the current structure of land use and water management, and how can these systems best adapt to future constraints on water resources? and (3) What are the key linkages between the biophysical and human components of the water system, and how do these linkages structure adaptation to water resource changes? The project involves a large interdisciplinary and multi-institutional team that spans the biological, ecological, economic, engineering, hydrologic, planning, policy, and social sciences. The work presented here addresses Question 3: the identification of linkages among components of the water system for the purposes of better understanding of responses to changes in water resources. This framework was used to refine and develop new sets of research questions and hypotheses and to synchronize related project activities and guide coordinated data collection efforts. The framework was also used to guide individual researchers in situating their particular research activities within the larger integrated project.

2.2. Framework Development

Framework development took place over a period of approximately 1 year and followed principles and best practices in conceptual and participatory modeling [*Langsdale et al.*, 2013] including: (1) involving all team members early and often to ensure their views were represented and (2) using an open and

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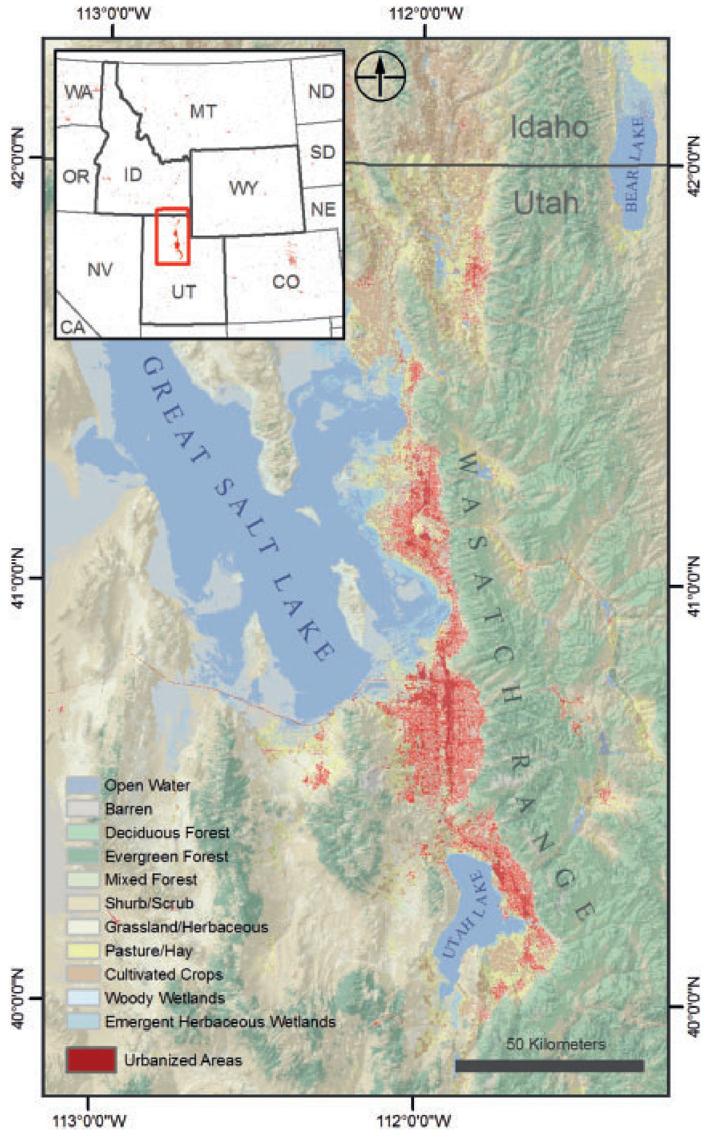

Figure 1. Wasatch range metropolitan area. Land cover data are from the National Land Cover Database [*Jin et al.*, 2013].

transparent development process. We achieved these principles through frequent in-person meetings and web-based conference calls. In-person meetings were held at different locations to allow team members from distant institutions to participate. Web-based conference calls were essential for more frequent meetings with larger groups, during which we were able to share documents and edit the framework.

A core group comprising the authors developed and wrote up the framework with core group membership open to all members of the larger project (more than 100 participants). Throughout the process, presentations and framework and manuscript drafts were shared with the larger group, along with invitations for feedback and participation. Initially, individual team members and small groups reviewed literature, examined project documents, and met to identify both the study system's principal components and linkages among the components. Next, these elements were organized into a draft conceptual diagram and presented to the full team for feedback. The presentation was followed by small group discussions and critiques of the framework, during which feedback was recorded and communicated to the organizers. The core group further developed the framework through a series of smaller, half-day workshops where the scope of major components was expanded and agreed upon, sub-components specified, and linkages

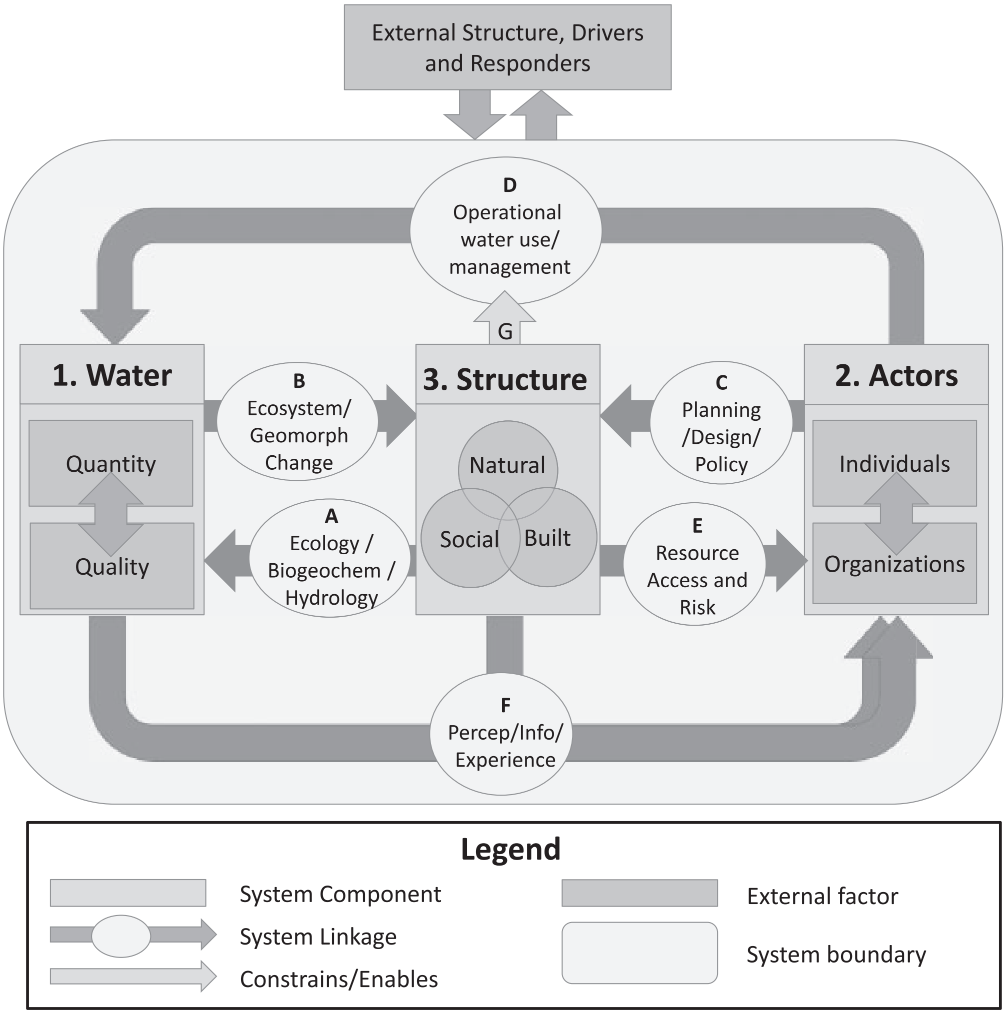

Figure 2. The iSAW conceptual framework is organized around three main structure, actor, and water components (gray boxes), seven key linkages (arrows), and a system boundary (light grey shaded box) that separates internal and external (box with dark shading) components.

and labels revisited to clarify meaning and remove redundancies. One important workshop exercise was to map ongoing water sustainability research onto the framework to confirm that the framework adequately represented key linkages and components of ongoing research and identify additional components or linkages that were missing. The team reached a consensus on the framework (Figure 2) when all participants agreed that no further changes were needed and that the accompanying text adequately described the components and linkages.

Since participant input was at the heart of the process of developing the framework, there is always the possibility that the individual biases of the participants shaped the structure, contents, and generalizability of framework. To ensure the framework provided specificity while maintaining generalizability across scales, domains, and participants' differing areas of expertise and interest, we involved a large and diverse set of participants. The framework underwent substantial changes as we iterated toward the consensus version presented in this paper. Working with a broad and diverse team required coordinating among a large number of people and finding a common language of communication; these challenges are often faced by other large, interdisciplinary, multi-institutional research projects [*O'Rourke and Crowley*, 2012]. Section 3 describes the final consensus framework, while Section 4 presents two examples of how the framework has been applied to ongoing research inquiries into key water issues.

3. The Framework

The iSAW framework consists of the key components and linkages of a coupled human–water system. Components represent major entities in the system: Water, Actors, and Structure. These components were identified from project documents as being the key drivers and responders that were common across project research interests and questions. As the iUTAH project focuses on water resource sustainability, water quality and quantity were common responders, and most research was designed to address the role of various types of structures (e.g., land use, built infrastructure, and ecosystem structure) and actors in affecting water quality and quantity outcomes. Although water is a part of the structure of the environment, we pull it out from structure to focus on the processes driving and responding to water quality and quantity. These components are connected by linkages that describe the hypothesized interactions among the major components.

3.1. System Components

Major components are enumerated by the numbers 1–3 on the diagram (Figure 2) and are underlined when first introduced in the text. Sub-components are italicized.

3.1.1. Water

Water includes diverse aspects of both water *quantity* and *quality*. In terms of water quantity, we consider how water is distributed in time and space. Metrics for water *quantity* include discharge in streams and canals; the volumes of water in lakes, reservoirs, and groundwater aquifers; and spatial and temporal distributions of water, including precipitation, floods, and droughts. Equally important is the *quality* of water, as measured by concentrations of pollutants, sediment, and limiting nutrients such as nitrogen and phosphorus, as well as bacterial or microbial populations that are related to human health or critical ecosystem processes. Metrics for water quality include the spatial and temporal distribution of concentrations and loads, including, for example, concentrations of nutrients along a montane to urban gradient or changes in concentrations of sediment from base flow to stormflow in a stream.

From an ecological perspective, water quality parameters of interest include: total suspended and dissolved solids, volatile suspended solids, dissolved organic carbon, dissolved inorganic nitrogen and phosphorus, total nitrogen and total phosphorus, and dissolved anions and cations. Loads (i.e., total amounts) of these constituents are useful for constructing constituent budgets to understand their sources and fates. Loads are also common metrics for water quality regulations (e.g., total maximum daily load [TMDL]) and are therefore targets for management. However, other possible contaminants are regulated based on their concentration (e.g., by the Environmental Protection Agency [EPA] Safe Drinking Water Act). The selection of metrics for water quantity and quality monitoring is specific to individual studies.

3.1.2. Actors

Actors represent the *individuals* and *organizations* within the study system boundaries that make water-related decisions, including operational (i.e., use and management) and planning, design, and policy decisions. Although we consider individuals and organizations separately, it is important to note the overlap between these categories. Organizations are made up of individuals, some of whom act as representatives of those organizations, and many of the interactions between organizations are through individuals. *Individuals* represent the smallest scale at which water management decisions and behaviors occur and include homeowners, residents, farmers, ranchers, business owners, community leaders, representatives of water management and governance entities, and others. The behaviors of individual actors within the water system can be driven by their objectives, knowledge, resources, beliefs, values, and attitudes, although the balance of these attributes is still understudied and may vary across systems [*Braden et al.*, 2009]. For example, several studies have identified concern about environmental problems (e.g., pollution, climate change) as a significant predictor of water conservation behaviors [*Domene and Saurí*, 2006; *Grafton et al.*, 2011], although others have found that attitudes were not as important as the physical infrastructure by which people use water [*Endter-Wada et al.*, 2008; *Kilgren et al.*, 2010]. Individual behaviors can also be affected by socioeconomic status [*Larson et al.*, 2009] and perceptions or concerns about what other people think [*Braden et al.*, 2009]. Individuals may also act as part of social groups (such as families, households, and neighborhood associations).

Organizations are groups of actors that come together for a common goal. These groups can include informal assemblages of individuals that are advocating on behalf of a specific water issue or more formal entities that have socially recognized water management, allocation, enforcement, or other responsibilities. Organizational actors span many scales of water management, from nongovernmental to municipal to state to federal to international. Organizational actors include government agencies, advocacy organizations (e.g., environmental groups, advisory committees), and various types of private organizations (e.g., homeowner associations, engineering firms, and irrigation companies). Organizational actions regarding water management have been considered from organizational theory [*Braden et al.*, 2009] and common pool resource perspectives [*Ostrom et al.*, 1999], both of which focus on how internal structures and rules within organizations affect water-related decisions. Less attention has been given to how water organizations are interconnected with one another across space and time (for an exception, see *Muñoz-Erickson et al.* [2010]).

3.1.3. Structure

Structure is a central component of water systems that shapes how water moves and water quality changes through the system, enables or constrains water decisions, and patterns water-related behaviors. We identified the following three types of structure as key to the water system: *natural* (e.g., stream channels, ecosystems, soils, topography, climate), *built* (e.g., land cover, building mix, landscaping, infrastructure), and *social* (e.g., demographics, laws, norms, culture). The structural components of the conceptual framework are illustrated as a Venn diagram to acknowledge that the boundaries between these three types of structure overlap considerably. We further discuss each of the structural components below.

3.1.3.1. Natural Structure

The *natural* component of structure includes the topography, geology, soils, climate, composition and distribution of biotic communities, and hydrology of the environment that have not been built by humans. While we recognize that the term "nature" is problematic, we use it here as a succinct term to describe all nonanthropogenic aspects of the system. Important water-related natural structure in Utah includes watershed topography, the spatial distribution of water bodies (streams, rivers, lakes, aquifers), soil structure, and the distribution and composition of plant communities. Some of these features (e.g., watershed-scale topography) are at the scale of the watersheds and are generally minimally affected by humans. Yet many aspects of *natural* structure have been altered by humans in often large and observable ways, such as biotic communities (e.g., directly via forest management and indirectly through changes in climate). As such, the *natural* sphere is deeply interconnected with the other two human structures (built and social).

3.1.3.2. Built Structure

Built structure represents the constructed features of the landscape that people design, create, operate, and maintain. *Built* structure can be considered across a range of scales, from outdoor irrigation systems used by homeowners to regional reservoir and canal systems used to store and deliver water. *Built* structure includes the constructed landscape of buildings, streets, and other impervious surfaces, as well as centralized or decentralized infrastructure for water supply, wastewater, and storm water conveyance, treatment, resource recovery, and reuse. Built structure also includes artificial groundwater recharge basins and extraction wells. In Utah water systems, built structure can be described by land use (e.g., urban, row crop agriculture, pasture, forest), land cover (e.g., imperviousness, landscaping types as these affect water use and energy balances), aspects of buildings such as distributions and heights (as these affect energy balances and therefore processes such as evapotranspiration), the distributions and designs of conventional and green storm water infrastructure (as these can affect water balances, nutrient cycling, and pollutant uptake and transformation), the distributions and designs of wastewater infrastructure (collection, treatment, and reuse systems), and the distribution and designs of water supply infrastructure, including reservoirs, canals, and aqueducts. In Utah, agricultural irrigation conveyance infrastructure is a dominant landscape feature and often interacts with systems for municipal supply and drainage.

3.1.3.3. Social Structure

Social structure refers to the relatively stable arrangements or relationships within society that systematically enable or constrain actors' behaviors. Culture and institutions interact to create *social* structure.

Cultural aspects of *social* structure include shared norms or understandings of how people should behave and attitudes and values that are shared among groups of people in a social setting. Institutional aspects of *social* structure refer to formal social arrangements such as property rights, laws, policies, programs, and organizational procedures, as well as less formal *social* structure such as families, ethnic or racial groups, interest groups, religions, and/or businesses. The stratification of members of society based on economic or other attributes into relative positions of power represents s*ocial* structural factors that influence (but do not determine) relative positions of power and capacity for action among actors. Water-relevant *social* structure in Utah (and much of the western United States) includes, for example, prior appropriation water rights law [*Huffaker et al.*, 2000], water pricing policies [*Olmstead et al.*, 2007], patterns of economic and social inequality [*Jenerette et al.*, 2011], social networks [*Muñoz-Erickson et al.*, 2010], and cultural norms with regard to residential landscaping and conservation behaviors [*Russell and Fielding*, 2010]. *Social* structure directly influences built and natural structure through jurisdictional boundaries that set how, where, and under what circumstances rules are applied to landscape and water systems [*Endter-Wada et al.*, 2009; *Lookingbill et al.*, 2009].

3.2. System Linkages and Constraining and Enabling Factors

In iSAW, system components interact through several types of linkages, which are labeled A–G in Figure 2 and described below. Structure plays a central role in the model because the key linkages between actors and water—water use (D) and perceptions (F)—are all enabled or constrained by the various configurations of natural, built, and social structure of the water system. We discuss this idea more fully below.

3.2.1. The Role of Ecology, Biogeochemistry, and Hydrology

The structure of the environment affects water quantity and quality outcomes via a range of ecological, biogeochemical, and hydrologic mechanisms (Figure 2, arrow A). Understanding the nature and extent of these processes is important for understanding outcomes of both water quantity and water quality. The distribution and composition of species, for example, influence water quality and quantity via effects on energy, water, and pollutant balances from plot scales [*Turnbull et al.*, 2008; *Bradford et al.*, 2014] to regional scales [*Creed et al.*, 1996; *LaMalfa and Ryel*, 2008]. While many of these processes have been well studied in natural systems, many aspects of the water balance and biogeochemical cycles are not well known in urban and agricultural systems [*Pataki et al.*, 2011a, 2011b; *Bain et al.*, 2012].

Hydrologic processes—i.e., precipitation, infiltration, runoff, and evapotranspiration—are directly related to features of the natural structure of the environment: topography, soil properties, vegetation composition and distribution, and climate. The built structure of the environment alters the balance of these processes through the explicit engineering of new flow paths (e.g., canals, storm drains), as well as through the modification of surface characteristics (e.g., impervious surfaces), microlimate (e.g., urban heat islands), and plant and soil communities [*Pataki et al.*, 2011b]. Engineered infrastructure can affect groundwater infiltration, evapotranspiration rates, or the transfer of water among basins, meaning that hydrologic models based on topography may not represent actual flows and fluxes of water in many highly engineered water environments [*Lookingbill et al.*, 2009].

Water quality is mediated by a wide range of biogeochemical processes, including nutrient uptake and transformations. These processes are controlled by soil properties, the physical and chemical conditions of the environment (i.e., presence of reactants and substrates as well as conditions necessary for reactions to occur), and biotic communities. Many of these processes are well understood in natural watersheds and soils [*Hedin et al.*, 1998]. However, transitions to agricultural and urban land use alter water quality via changes to both material transport pathways and opportunities for biogeochemical transformations [*Groffman et al.*, 2002, 2003]. Furthermore, urban and agricultural environments create novel biogeochemical settings (e.g., high inputs of nutrients in combination with pesticides in agricultural streams, or heavy metals in urban streams) [*Bernhardt et al.*, 2008] that are different than well-studied natural systems and which may not conform to models of ecosystem function developed in nonhuman-dominated systems. Finally, many aspects of the built environment are designed to alter water quality, such as potable water or wastewater treatment facilities and storm water control systems. The degree of treatment of potable water and wastewater and the types and distribution of storm water control measures have important implications for water quality as well as water quantity within a given hydrologic setting.

3.2.2. Ecosystem and Geomorphological Change

While many processes and feedbacks in this coupled human–water system occur through the decisions or behaviors of actors, water quantity and quality outcomes may directly affect natural components of structure via ecological or geomorphological feedback processes (Figure 2, arrow B). For example, flood conditions may alter geomorphological structure through the erosion and redeposition of sediment, and this altered geomorphology may then affect the distribution of aquatic and riparian biota [*Swanson et al.*, 1998]. Research in semi-arid ecosystems has suggested that water quantity and quality conditions may act as a positive feedback to natural structure, reinforcing vegetation patterns through the distribution of nutrients, water, and sediment [*Turnbull et al.*, 2008]. Another example is the effect of soil water conditions on vegetation establishment, where long-term changes in hydrologic variables such as snowpack (e.g., due to climate change) may lead to changes in vegetation communities [*Kelly and Goulden*, 2008]. Furthermore, as flow regimes in rivers and streams change due to natural or anthropogenic forces (e.g., climate change, water development, or land cover change), sediment transport and fluvial landforms are also altered to bring these systems toward equilibrium. These processes affect riparian vegetation communities, in-stream habitat, aquatic assemblages, and cycling of nutrients and organic matter [*Brierley et al.*, 1999]. In regions where increasing air temperatures are anticipated to shift precipitation from snowfall to rainfall, hydrographs will likely become flashier with more frequent, larger winter storm pulses and longer, warmer summer conditions [*Null et al.*, 2010]. Variable precipitation and runoff could then, in turn, increase erosion and sediment transport during winter in some reaches [*Carpenter et al.*, 1992]. Warmer summer stream temperatures from climate change could also be expected to affect photosynthesis and respiration in streams [*Carpenter et al.*, 1992], the distribution of fish and aquatic organisms, and riparian communities [*Yarnell et al.*, 2010; *Null et al.*, 2013]. These ecological and geomorphological feedbacks may only be important for built and social structures in extreme cases (e.g., major floods or storms). Most of the feedbacks from water to social and built structure are expected to occur indirectly through social mechanisms (see arrows C and F) as actors perceive and adapt to changes in the natural structure.

3.2.3. Planning, Design, and Policy

While much of the social-built-natural structure in any given water system enables or constrains different forms of water decision-making over the short term, individual and organizational actors actively make planning, design, and policy decisions, including decisions about governance, that shape the natural, social, and built structure of the environment over medium and long terms (Figure 2, arrow C). These decisions occur at and across a wide range of scales. For example, homeowners decide how to landscape their property, cities determine pricing of their water supplies, water districts plan infrastructure improvements, and interest groups engage with policymakers regarding water rights law and water quality policies.

Actors engaged in forest and watershed management, or those enforcing land-use regulations, make decisions that can lead to transformative changes in both social and natural structure. For example, in response to severe flooding and erosion during the 1930s in Utah, the Forest Service implemented new policies of reforestation and erosion control measures (i.e., social structure). These new policies changed Forest Service land management practices that in turn altered the composition and distribution of vegetation in the surrounding mountains (i.e., natural structure) [*Flores*, 1983]. Logging activities also alter forest structure, while the diversion of water through designed regional and local reservoir and canal systems also affects the geomorphological and ecological structure of streams by altering flow regimes.

Built structure is created by actors and is affected by a range of actions, such as homeowner landscaping choices, local zoning decisions, and reservoir planning. At the watershed scale, local water organizations, including municipalities and water conservancy districts, make key decisions regarding the construction and maintenance of irrigation, potable water, wastewater, and storm water infrastructure in Utah. Planning conducted by municipal organizations directly impacts the built environment through permitting and zoning [*Nelson*, 1978] and by setting policies such as urban growth boundaries [*Bracken*, 2007]. More generally, individual and organizational actors frequently make decisions to build new infrastructure, repair existing infrastructure, or decommission aging infrastructure.

Actors can also affect social structure through lobbying, voting, policy making, and other collective efforts to alter knowledge and behavioral norms about water use, allocation, and management [*Endter-Wada et al.*, 2009]. Regulatory actors, such as state agencies, enforce water rights and water laws, while policymakers, including legislators, author legislation pertaining to water allocation and usage, conveyance, and safety.

Social structure, actors' access to resources, and the risks they face critically influence actors' abilities to innovate and change policy, system designs, and planning processes. Changes in policy, design, and planning are often intertwined and the existing built and social structure of the environment favors the status quo, often serving as a barrier to adaptation. Innovations may be difficult when costs and resulting system performance are uncertain. [*Roy et al.*, 2008; *Brown and Farrelly*, 2009]. However, most impediments to innovation are social. Innovations may face barriers of social acceptance, such as the reuse of reclaimed wastewater. Change in the built structure of the environment frequently entails changes to the social structure, particularly when shifting from centralized to decentralized designs. These changes may require new institutional and governance frameworks, development of new standards and regulations, and allocation of responsibilities that can alter the distribution of costs and benefits within society [*Roy et al.*, 2008; *van de Meene et al.*, 2011].

3.2.4. Operational Water Use and Management

Given a particular structural context, actors affect water quantity and quality directly via their operational water use and management decisions (Figure 2, arrow D). At the smallest scale, individual decisions about indoor and outdoor water use (both residential and agricultural) can be aggregated to comprise the "demand" for water that directly impacts the quantity and quality of water in the system across temporal and spatial scales. Individual homeowners, residents, farmers, and ranchers make water use decisions, such as when and how to irrigate their property. These individuals also decide how much fertilizer to apply to their landscape and how to dispose of unwanted substances such as paint and pharmaceuticals—decisions with implications for water quality. At larger scales, short-term operational decisions about the management of built water systems by municipalities, conservancy districts, and reservoir managers also have a direct influence on patterns of water availability and use. The volume, timing, duration, and purpose of operations depend on the goals of the actor and intended water use(s) [*Loucks et al.*, 2005]. For example, an irrigation company may divert river water during the summer to allow farmers to irrigate, whereas an environmental organization may prefer the diversion of water in the fall low-flow season to maintain wetland or in-stream habitat [*Downard and Endter-Wada*, 2013; *Welsh et al.*, 2013].

Nearly all water management decisions by actors are enabled or constrained by the natural, built, and social structure that surrounds them. These linkages are discussed in Section 3.2.7.

3.2.5. The Role of Resource Access and Risk

The structure of the environment—natural, built, and social—affects actors' access to resources and the risks they face (Figure 2, arrow E). Resources include a wide range of materials, information, knowledge, and social and financial capital. Access is determined by sets of norms, rules, physical proximity, and other attributes of structure. Structure shapes which actors (individual or organizational) can use resources when and in what quantities. For example, individual water right allocations, as well as state-determined allocation caps, define access to water resources. At the same time, information can be limited by the structure of knowledge systems available to actors (e.g., policy makers do not commonly have access to scientific journal articles). Norms also determine how resources are used [*Ostrom et al.*, 1999]. For example, covenants, codes, and restrictions set by homeowner associations or municipalities set limitations on landscaping by homeowners or determine the types of storm water management systems that can be built in new developments. In this way, social structure interacts with natural and built structure to enable or constrain individuals' and organizations' access to material resources as well as their ability to act or change related structures [*Larson et al.*, 2009].

Risk refers to the combined magnitude and probability of loss (e.g., of life or property) actors may experience from uncertain conditions manifested through natural, built, and social structure [*Eakin and Luers*, 2006]. Actors also have varying exposure, sensitivity, and capacity to adapt to these risks [*Eakin and Luers*, 2006; *Zahran et al.*, 2008; *Eakin et al.*, 2010]. For example, the risk of loss due to flooding is influenced by natural structure, such as topography and hydrology, and built structure, such as reservoirs and levees, storm water drainage, and housing construction and contents. The risk of loss from flooding is also influenced by the presence or absence of social structures such as flood mitigation policies and actors' access to social and political resources [*Zahran et al.*, 2008; *Eakin et al.*, 2010]. Risk of loss of life and property has also been tied to properties of the actors themselves, such as socioeconomic status. For example, minorities and the poor are less likely to receive, believe, or be prepared for emergency warnings, less likely to evacuate during emergencies, or to have flood or emergency insurance. These communities are also more likely to live in high-risk areas [*Zahran et al.*, 2008; *Eakin et al.*, 2010]. Other important water-related risks include (but are not limited to) water scarcity and drought, water pollution, and the loss of economically important ecosystems due to water pollution [*Endter-Wada et al.*, 2009; *Srinivasan et al.*, 2012].

3.2.6. The Role of Perceptions, Information, and Experience

With respect to water-related behaviors, the decisions of water actors are fundamentally shaped by their awareness of water quality and quantity and the structure of their water system (Figure 2, arrow F). Awareness is represented by the perceptions, information, and experiences (PIE) that encompass the many ways in which actors become aware of and make sense of their world. Perception refers to how people interpret sensory information, such as the high water mark during a flood or the taste of drinking water. Experience refers to observational knowledge gained from involvement with or exposure to something or some event, such as basement flooding during snowmelt events or the loss of crops as a result of drought. Information is knowledge obtained through more formal channels such as formal education, scientific instruments and sensors, publications, mass media, or the “situated knowledge” of laypeople or nonscientists [*Irwin*, 2001; *Endter-Wada et al.*, 2009]. Thus the PIE arrows represent feedbacks that actors receive from the water system and incorporate into their decision-making.

Social structure can significantly enable or constrain the flow of information to different actors. Most actors are not fully aware of the water system and make decisions with limited, imperfect, and uncertain information. Actors enabled by structure can influence the water system knowingly, based on how they perceive and experience water and make sense of related information. Actors can also influence water inadvertently or without direct intent. Actors’ water decisions frequently reflect incomplete awareness of the status of or changes in water quality and quantity. Indeed, many water system outcomes reflect the unintended consequences of choices made with limited and contextualized information about the larger integrated water system.

3.2.7. Structural Impacts on Actors

In our conceptual model, actors make important water management decisions seeking to have direct effects on water quantity and quality. As noted above, people do not act in a vacuum, and their operational water management decisions are enabled or constrained by the natural, built, and social structure of the environment. Our framework thus includes a “constraining/enabling” arrow from structure to water management (Figure 2, arrow G) that reflects the ways in which different configurations of structure affect water management decisions and behaviors.

For example, individuals and organizations operate the built structure by specifying the timing, volume, and duration of diversions, withdrawals, releases, and treatment. Typically, these operations are constrained by the physical attributes of the existing built structure such as location, capacity, and operational costs. Similarly, at the parcel scale, residential and institutional landscape irrigation is strongly related to the built landscape including the technology used to apply the water, as when manual hand watering leads to more water conservation than programmed sprinklers [*Endter-Wada et al.*, 2008; *Kilgren et al.*, 2010]. Social structure at many scales also affects operations and management. For example, state prior appropriation law defines the volume, timing, and location of all water withdrawals as well as the beneficial use(s) to which water can be put. The range of people’s water use decisions is constrained by water law and negotiated settlements within the legal structure [*Endter-Wada et al.*, 2009]. At the neighborhood scale, social norms such as when nearby urban or agricultural users can divert water from a canal can influence individual water behaviors [*Endter-Wada et al.*, 2008]. The cultural and institutional dimensions of social structure generate lines of social difference (e.g., class, race, and gender) that affect the relative power held by different individuals and groups depending on their social position and have consequences for the distribution of water resources and the ability to make and implement water-relevant management decisions [*Molle*, 2007]. For example, farmers who have historically used irrigation system water may be allowed greater flexibility in their water use decisions than residents of newly constructed housing. Although not illustrated in the diagram, all components of structure can also constrain the perceptions, information, and experiences of actors, as noted above in Section 3.2.6.

3.2.8. External Structure, Drivers, and Responders

No study system is isolated, and human–water systems interact with numerous external structures, drivers, and responders (Figure 2). We define as external any variables that differ from the study system in: (1) spatial scale, (2) location, (3) time, or (4) domain. In terms of geographic scale, changes in markets, law, policy, or climate at the state, regional, national, or global scale can have important implications for a watershed-scale system but are best viewed as exogenous to the core dynamics of the water system in our framework. While we are used to thinking of processes at different spatial and temporal scales as being external drivers of a study system [e.g., *Peters et al.*, 2007], systems at the same spatial scale but separated in space may also act as external drivers through flows of material, information, or people. These systems are often referred to as "teleconnected" [*Adger et al.*, 2009; *Seto et al.*, 2012]. For example, dust from a distant ecosystem deposited on local snowpack can alter the timing of snowmelt [*Painter et al.*, 2007, 2010]. Legacies such as historic land-use patterns, for example, have been shown to be important drivers of ecosystem structure and function [*Foster et al.*, 2003]. A similar concept is that of path dependence, which suggests that system trajectories are self-reinforcing and therefore contingent on past states [*Pierson*, 2000; *Martin and Sunley*, 2006]. Water systems are also affected by processes occurring in other domains. A key example of this is the water-energy nexus, which describes the energy cost of treating and distributing water and the water cost of producing energy [*Sovacool and Sovacool*, 2009; *Abdallah and Rosenberg*, 2014]. With population growth and increased demands for both energy and water, energy sector is expected to place a larger demand on water supply and supplying water will require higher energy inputs [*Sovacool and Sovacool*, 2009; *Utah Division of Water Resources*, 2012]. Finally, external variables can also be responders in addition to drivers—for example, irrigation, by reducing local air temperatures through evaporation, can feed back to alter larger scale climate patterns [*Lobell et al.*, 2009; *Puma and Cook*, 2010]. External drivers may interact with or affect any or all aspects of water systems. For example, external climate patterns can affect water quantity or quality outcomes by altering hydrologic and biogeochemical processes (e.g., by altering snowpack, or temperature changes may alter rates of key biogeochemical processes). Climate can also affect water outcomes via changes to actors' perceptions of water scarcity and, therefore, water use patterns. Because our framework is designed to be general and applicable across scales, features that are internal to one study system may be viewed as external drivers in another. Important external drivers with regard to water systems could include: climate, ecological disturbances, human population and demographic shifts, economics, and regulations.

4. Applying the Framework to Research Examples

We present two case studies in which we have applied the framework to Utah-focused research activities and show how the framework helped to generate new, overarching interdisciplinary research questions, formulate hypotheses, and synchronize project activities including data collection to test the hypotheses. In the case studies, the framework also allowed researchers to situate their individual research activities within the larger project and water system. The two case studies are: (1) understanding urban water supply and demand in a changing climate and (2) expanding use of green storm water infrastructure in a semi-arid environment. Our discussion of these cases in the text focuses on highlighting the application and utility of the framework in deepening and broadening the resulting research questions. Tables 1 and 2 compare previously defined research questions with those generated after using the framework.

4.1. Urban Water Supply and Demand in a Changing Climate

Managing changes in water supply and demand is a major challenge facing decision-makers in the urbanizing American West. Increasing urbanization and corresponding changes to agricultural land use are affecting demand for potable and irrigation water [*Udall*, 2013]. Meanwhile, a shift in precipitation from winter snow to rainfall, coupled with an earlier snowmelt, has significant implications for the timing and volume of water supply and water availability [*Barnett et al.*, 2008; *Gillies et al.*, 2012]. The scope of water supply and demand research is broad, spanning many disciplinary perspectives and scales. Here, we focus on two aspects of urban water supply and demand research to illustrate how the application of the iSAW framework can identify new research questions and hypotheses. Specifically, we map onto the framework both

Table 1. Research Questions Addressing Water Supply and Demand Before and After Consideration of Framework

Linkage	Proposal Research Questions	Research Questions Generated From Framework	What Did iSAW Add?
EXTERNAL: Climate	Q1. How will availability of montane water resources change as a result of climate change (via timing and amount of snowpack)? Q2. How will climate change affect forest composition and risk of fire and beetle infestation?	Q18. How will climate change affect water demand (biophysical and social mechanisms)?	Broader conceptualization of climate impacts on all aspects of the system, including actors' perceptions/attitudes/behaviors/etc., in addition to biophysical implications. Effects of climate on water demand could be complex, via both social and biophysical mechanisms.
EXTERNAL: Teleconnections	Q3. How will dust deposition affect the timing and amount of water supply? Q4. How will deposition of N and other pollutants affect the quality of the water supply? Q5. How will demand for montane water resources change as a result of land-use change?	Q19. How will competing demands affect water supply?	
A. Ecol-ogy/Biogeochem/Hydrology	Q7. How are forest water balances affected by forest vegetation composition? Q8. How are snowmelt, runoff generation, infiltration, ET, and deep percolation affected by elevation, microclimate, and land cover? Q9. How is local-scale ET affected by climate, water stress, phenology, management practices, and species composition? Q10. How does land use affect the transport and processing of nutrients, major cations and ions, and particulates?	Q21. How does watershed structure (soils, vegetation, snowpack) affect water balance and supply? Q22. How does distribution of reservoirs (storage) and canals (delivery) affect water supply?	Focus in proposal was ecohydrologic control on water supply, framework broadens to take into account social and built environment controls on water supply, as well as other aspects of natural structure beyond vegetation. Social structures such as water rights can have significant effects on water supply to actors, and distribution and storage systems are critical for predicting water supply.
B. Ecosystem and geomorphological change	Q11. How do hydrologic conditions feed back to forest composition?		
C. Planning/Design/Policy	Q12. How do objectives, knowledge, resources, and beliefs of actors affect land and water management decisions?	Q23. How do actors alter social, built, and natural structure to affect desired water outcomes?	Broader conceptualization of decision-making, including creation and alteration of social, built, and natural structure. Separates decisions about structure from decisions about water use.

10.1002/2014EF000295

Table 1. (continued)

Linkage	Proposal Research Questions	Research Questions Generated From Framework	What Did iSAW Add?
D. Operational Water Use and Management	Q13. How is water used by agricultural and urban users?	Q24. How are reservoirs and canals managed to deliver water to users?	Consideration of multiple scales of operation and water use behaviors
	Q14. How do objectives, knowledge, resources, and beliefs of actors affect land and water management decisions?		
E. Resource Access	Q15. How does resource access affect decisions and behaviors of actors?		
F. Percep-tions/Information/Experience	Q16. How do actors respond to changing environmental conditions?	Q25. How do PIE regarding water scarcity and quality affect attitudes and behaviors of individuals and organizations?	Framework recognizes that actors' responses to changing environmental conditions are dependent upon their perceptions of, information about, and experiences of those conditions.
G. Structural constraints on water use/management	Q17. How do population density, parcel size, land cover, water and built infrastructure, microclimate, and landscaping practices affect water use?	Q26. How does social structure affect water access and water use?	Broadens this constraint/enabler to consider both water supply and demand, includes social structure.

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Table 2. Research Questions Addressing Storm Water Green Infrastructure (GI) Before and After Consideration of Framework

Linkage	Strategic Plan Research Questions	Research Questions Generated From Framework	What Did iSAW Add?
EXTERNAL: Climate		Q4. How does climate affect the function of storm water GI?	Consideration of external drivers: federal regulations are a major part of storm water management, climate is an important part of GI function, and legacies could be a major barrier to change.
EXTERNAL: Regulations		Q5. How do regulations affect the adoption of storm water GI?	
EXTERNAL: Legacies		Q6. How do infrastructure and land-use legacies affect the adoption and use of GI?	
A. Ecology/Biogeochem/Hydrology	Q1. How do implementations of GI impact hydrologic processes (water pathways; water quantity and quality)? Q2. What are the best GI designs to enhance sustainability?	Q7. How does local climate affect the function of GI?	Consideration of role of local climate: infrastructure and climate interact to produce storm water outcomes.
C. Planning/Design/Policy	Q3. What are the major barriers and paths to implementation of GI?		Original question was vague. The framework allowed us to focus several related research questions to identify what those barriers and pathways are.
E. Resource Access		Q8. How does access to resources (political, social, financial) affect the ability of actors to implement GI? Q9. How do local regulations affect the adoption of GI?	Resource access is key to understanding barriers and pathways—infrastructure is expensive and requires political will to spend the money.
F. Perceptions/Information/Experience		Q10. How do PIE about flooding and storm water quality affect individual and organizational perspectives on GI and flood/pollution risk?	Another specific aspect of barriers and pathways—research on historical transitions in storm water infrastructure illustrate that flooding problems—people's experiences—were a major pathway toward installing a centralized storm sewer system.

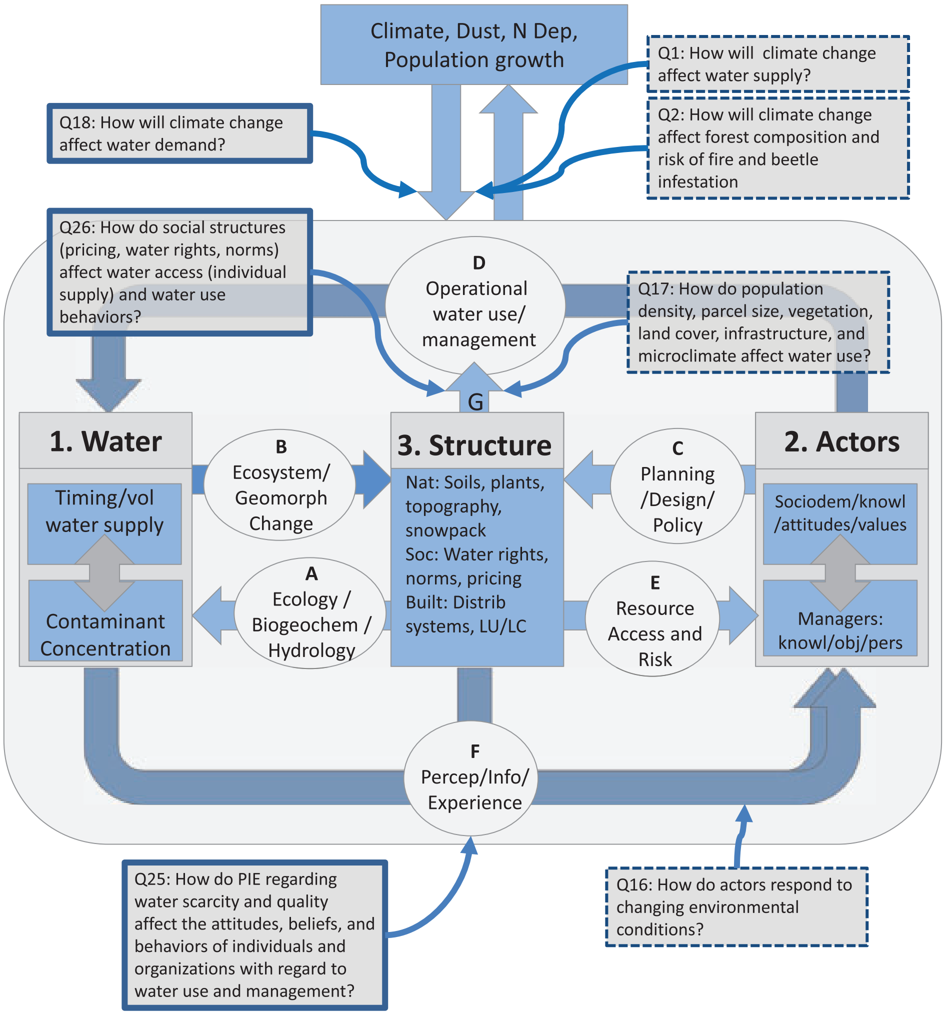

Figure 3. Research questions for water supply and demand overlaid on the iSAW framework. Questions in boxes with dashed borders are the original project research questions developed before the framework, whereas questions in boxes with solid borders were generated using the framework. Only the questions addressed in the text are shown (see Table 1 for a complete list of research questions).

the (i) original project questions regarding water supply and demand in the study region within the framework and (ii) the additional questions that emerged while researchers worked with the framework (Figure 3, Table 1). The comparison shows the value added by the framework to conduct more synthesis-oriented and integrated water supply and demand research.

A major focus of prior water supply and demand research and our original research questions was understanding the role of external drivers—particularly climate changes as they affect the supply of water [*Vörösmarty et al.*, 2000; *Barsugli et al.*, 2012; *Bardsley et al.*, 2013; *Udall*, 2013] and urbanization and population growth as they affect the demand for water resources [*Vörösmarty et al.*, 2000; *Udall*, 2013]. As mentioned above, in Utah and the Intermountain West in general, climate change is anticipated to have important consequences for water supply. Thus, the original project research questions asked: How will water resources change as a result of climate change via changes to the timing and amount of snowpack (Figure 3 and Table 1, Q1)? and How will climate change affect forest composition and the risk of fire and beetle infestation (Figure 3 and Table 1, Q2)? However, by examining regional water supply and demand within the context of the iSAW framework, we identified an additional research question of how climate would affect water *demand* (Figure 3 and Table 1, Q18). Importantly, climate changes could affect water demand through both biophysical and social mechanisms. Climate can exacerbate the microclimate effects of urbanization (often referred to as the “urban heat island” effect), increasing evaporative demand and the need for outdoor irrigation [*Bardsley et al.*, 2013]. Climate change could also affect water demand if actors' perceptions, information, and experiences of climate change affect their water-related behaviors [*Barsugli et al.*, 2012]. These behaviors could include watering and landscaping behaviors of urban residents, changes in water infrastructure systems (e.g., reservoirs, inter-basin transfers), and changes in formal or informal water law, policy, or institutions. By recognizing that actors' perceptions and behaviors may shift in response to climate (in addition to biophysical changes), researchers can take a more comprehensive approach to addressing how climate affects all aspects of the system. In this example, the iSAW framework allowed the project team to consider a broader set of climate impacts on the integrated system.

Another original research question addressed how natural and built structure affected water management: How do population density, parcel size, vegetation, impervious surfaces, water and built infrastructure, microclimate, and landscaping practices affect water use (Figure 3 and Table 1, Q17)? Previous research has shown that water use at the city or neighborhood scale is dependent upon these physical features of urban form [*Shandas and Parandvash*, 2010; *Grafton et al.*, 2011; *House-Peters and Chang*, 2011; *Stoker and Rothfeder*, 2014]. As we applied these research questions to the iSAW framework, we observed that we could go beyond natural and built structure to also investigate the role of social structure by asking: How does social structure affect water access (i.e., supply) and therefore water use behaviors (i.e., demand) (Figure 3 and Table 1, Q26)? Delivery systems, water pricing, and water rights law can act as enablers or constraints on actors' water use and management decisions by limiting their physical or legal access to water—i.e., their water supply [*Huffaker et al.*, 2000; *Hearne*, 2007; *Welsh et al.*, 2013]. For example, high water prices can limit the effective supply of water for those who are unable to pay [*Ruijs et al.*, 2008]. Water use—i.e., demand—is also likely to be affected by social structures, including norms [*Endter-Wada et al.*, 2008; *Russell and Fielding*, 2010] and water pricing [*Olmstead et al.*, 2007; *Klaiber et al.*, 2014]. For example, social norms have been shown to be significant predictors of attitudes toward water conservation and intentions to use less water or install water-efficient appliances [*Russell and Fielding*, 2010]. In this example, the framework allowed researchers to build upon existing research linking water demand and urban form to consider aspects of social structure as an enabler or a constraint of both water supply and water demand.

Overall, we used the iSAW framework to more broadly delineate the external drivers and explore how they might affect all aspects of the integrated system. We also found that by considering natural, built, and social structure components of the system, we can more explicitly link and describe the interplay between water supply and demand in the coupled system. With this synthesis view, the iSAW framework helped guide the development of specific research questions and data collection.

4.2. Green Storm Water Infrastructure in a Semi-arid Region

Green infrastructure (GI) is the decentralized, interconnected networks of natural and constructed plant–soil systems within, around, and between urban areas [*Tzoulas et al.*, 2007]. GI can include many aspects of the urban environment such as open space, parks, green roofs, storm water and wastewater conveyance and treatment systems, distributed energy generation, and riparian areas. For the purposes of this example, we focus on GI to manage storm water, which includes features such as retention and detention basins, treatment wetlands, green roofs, green streets, rain gardens, and bioswales. Storm water GI is used for a range of management objectives, including reducing storm water flow (either by detaining or infiltrating storm water runoff) and managing storm water pollution through biogeochemical treatment [*National Research Council*, 2008; *Davis et al.*, 2009; *Houdeshel et al.*, 2012].

There is widespread interest to expand the use of GI for storm water management by academics, practitioners, and the EPA [*Davis et al.*, 2009; *Houdeshel et al.*, 2012]. However, most of the research on storm water GI has been conducted in humid regions, and there is limited information about how these systems function in semi-arid environments such as Utah [*Davis et al.*, 2009; *Houdeshel et al.*, 2012]. Furthermore, there is little understanding of the barriers and opportunities that exist for implementing GI or transitioning existing storm water systems to GI [*Brown et al.*, 2013; *Keeley et al.*, 2013; *Schaeffler and Swilling*, 2013]. The original objectives of our GI research focused on understanding: (1) how GI designs affected water quality and quantity outcomes, (2) how to design GI for sustainability, and (3) identification of the barriers and paths to GI implementation (Figure 4). Similar to the water supply and demand example, the iSAW framework helped refocus and facilitate more integrated research to identify the: (1) external drivers of the integrated GI system and (2) mechanisms affecting GI implementation.

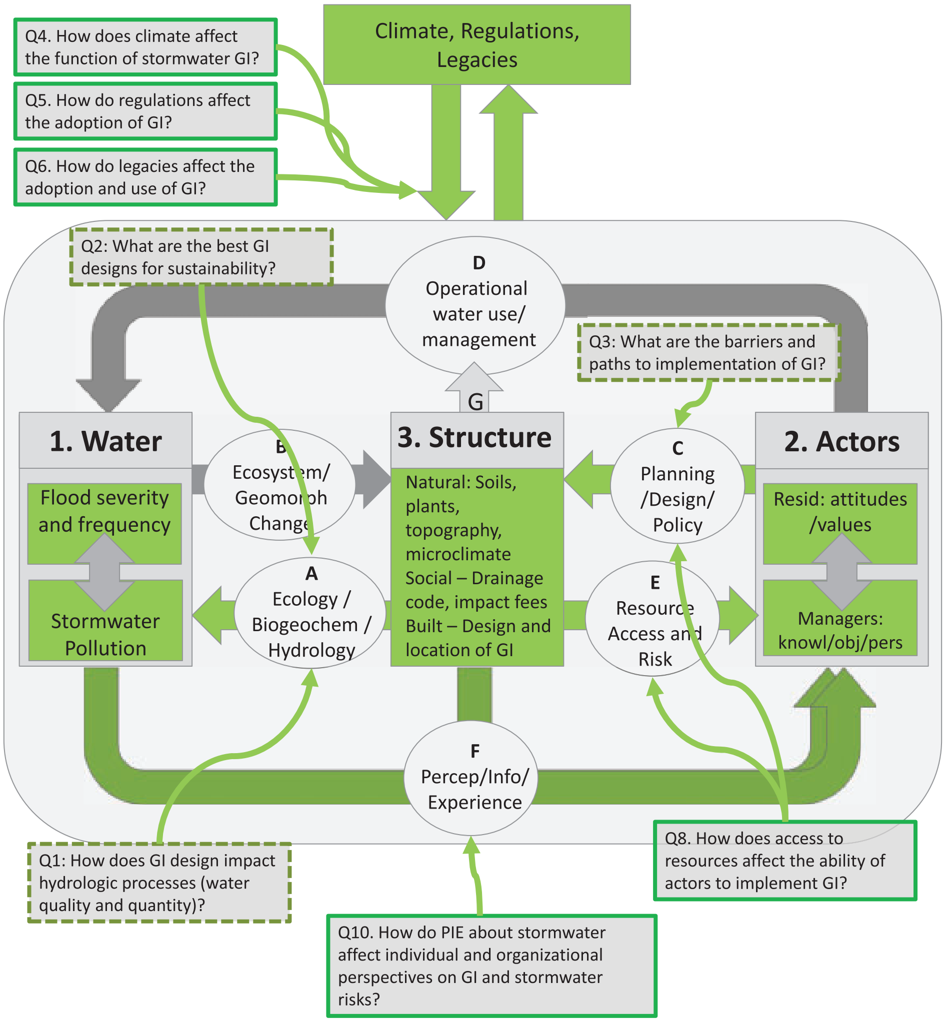

Figure 4. Research questions for storm water green infrastructure (GI). Questions in boxes with dashed borders are the original project research questions developed before the framework, whereas questions in boxes with solid borders were generated using the framework. Only the questions addressed in the text are shown (see Table 2 for a complete list of research questions).

Our original research questions listed in the project proposal did not address the importance of external drivers to the use and performance of GI (Figure 4 and Table 2). As we applied these questions to the iSAW framework, we identified external drivers that were likely to be important factors shaping both GI function and implementation (Figure 4 and Table 2, Q4–Q6). For example, climate variation, either within an urban area or over time, could have important implications for GI function (Figure 4, Q4). Consideration of climate is also important for designing locally appropriate infrastructure, and a key challenge in arid regions is to design GI features that can adequately address storm water quality and quantity, while minimizing the need for irrigation to maintain vegetation between storms [*Houdeshel et al.*, 2012]. To test GI designs and understand the mechanisms linking design to storm water quantity and quality outcomes, project researchers are using a combination of controlled experimental research and *in situ* observation of GI in the urban study areas (Table 2, Q1). Here, the research questions focus on how built structures (the storm water GI itself) and natural structures (i.e., soil infiltration capacity, vegetation) interact to shape water quality and quantity outcomes. Previous research has found that external drivers, such as storm characteristics, can have important implications for watershed-scale nutrient retention in arid cities [*Lewis and Grimm*, 2007; *Hale et al.*, 2015]. Although there have been no studies specifically looking at GI performance across different climate conditions, both precipitation and temperature are expected to affect GI water balances (e.g., via evapotranspiration) and biogeochemical transformation rates.

A different set of external drivers are also likely to be important for understanding the pace and location of GI implementation. Storm water policies [e.g., *U.S. Environmental Protection Agency* (*US EPA*), 2014] could encourage cities and private actors to adopt GI (Table 2, Q5). Infrastructure legacies, on the other hand, could be a major barrier to GI implementation (Table 2, Q6). In large cities with extensive, well-established storm water infrastructure (e.g., storm sewer networks), there are technological, financial, and institutional barriers to transitioning to a decentralized GI system [*Keeley et al.*, 2013]. Legacies are also important for understanding current storm water systems. For example, in many cities throughout Utah, irrigation canals also serve as de facto storm water drainage ditches and have (often unintentionally) become a defining feature of municipal storm water systems.

A second original research objective was to understand barriers and pathways to GI implementation (Figure 4, Q3), but the project's original hypotheses about the mechanisms of infrastructure transitions were underdeveloped. In our conversations about the application of the iSAW framework, we developed several hypotheses and more specific research questions that explore how three system linkages might influence the adoption of GI: (1) resource access, (2) perceptions, information, and experience, and (3) external drivers. Resource access could shape infrastructure transitions in that infrastructure is expensive, and, as a result, building infrastructure requires both financial capital and political support. In Utah, for example, small cities with limited staff or budgets (i.e., social structures) tend to use GI in new residential and commercial developments, where developers fund the use of these infrastructures. The perceptions, information, and experiences of residents and storm water managers regarding storm water and GI can be either a barrier or a pathway to GI implementation. One ongoing research project on historical transitions in storm water infrastructure shows that flooding problems (i.e., people's experiences) were a major motivation toward installing a centralized storm sewer system (Hale, unpublished data). On the other hand, transitions are unlikely to occur when residents and managers are not aware of or concerned about problems with storm water quality or quantity. These linkages have informed our data collection efforts and a project working group is currently conducting surveys of storm water managers and households to understand how these two groups of actors perceive GI and whether they see or have experienced risk associated with storm water quantity or quality.

As illustrated in Table 2 and Figure 4, our original conception of storm water was narrow and focused on implementation, design, and function. Exploring GI within the context of the iSAW framework helped develop specific hypotheses regarding GI implementation (Q8 and Q10, Figure 4) while also suggesting mechanisms for feedback between GI function and implementation (Q10, Figure 4). Furthermore, considering all GI research within the iSAW framework has facilitated connections between social (transitions to GI) and engineering (design of GI) aspects of the research. For example, results from storm water manager surveys and interviews have grounded storm water GI design research in the real constraints experienced within Utah municipalities (e.g., operations and maintenance costs, desire to be a good steward). Absent this connection to local survey research, work on GI design would have relied on existing information about the experiences of managers from more humid or larger cities. As with the water supply and demand example, the iSAW framework helped develop more targeted research questions, facilitating research coordination and data collection.

5. Applicability to Other Locations and Issues

While iSAW was developed within the context of Utah water issues, the framework can be readily applied to other regions and natural resources. As illustrated by the water supply/demand and GI case studies, the framework is sufficiently flexible to be applied across scales and domains. It can also be applied to other natural resource issues, substituting the resource of interest (e.g., timber, energy, carbon, mineral resources, or an individual species) for water. In building the framework, we note that water is a part of the structure of the environment, but it has been made distinct from structure to highlight the quantity and quality subcomponents and how they are measured, as well as the relationships that are most important for water resources research. Frameworks organized around other resources could simply choose different sub-components and relationships to pull out from structure and emphasize. Regardless of the resource or focus, the framework highlights the importance of interdisciplinary research in natural resources and facilitates communication and interaction among different domains and scientists.

6. Conclusions

Water systems face many challenges in response to urbanization and climate change, including shifting societal expectations, new regulations, increasing water demand, and ecosystem changes. More sustainably managing water systems requires better understanding of the complex components and linkages in these coupled systems. Despite a wealth of literature on human–water interactions, it can be difficult to integrate this research across disciplinary perspectives. Coupled systems projects have struggled to systematically incorporate social and natural scientific theories related to the roles of social, built, and natural structures vis-à-vis the behaviors and decisions of key actors. Our framework advances upon previous conceptual models of human–water systems by recognizing diverse actors and the complex behavior that emerges from their individual actions and interactions as opposed to imposing aggregate- and community-scale responses to the human system. Furthermore, our work provides an elaboration of how the social aspects of coupled water systems should be represented not only by the behaviors of individual and organizational actors but also specifying how their actions shape and are shaped by their integrated social-built-natural structural contexts.

As a generalized conceptual model that identifies key biophysical and social components and linkages, the iSAW framework provides a roadmap for coupled human–water systems research and can help guide future interdisciplinary research to address water management problems and other natural resource issues. Importantly, by designing the framework to be generalized, we have identified mechanisms of human–water interactions that transcend domains and scales. In our own project, we found that a shared conceptual framework was important to facilitate interdisciplinary collaborative research. Further, by applying the framework to two case studies involving understanding water supply and demand in the face of changing climate and promoting GI in an arid climate, the iSAW framework allowed project researchers to develop much richer and synthesis-oriented research questions and hypotheses and formulate project and data collection activities to start testing the generated questions. The two case studies also illustrate the utility of the iSAW framework to: (1) develop a broader and deeper conceptualization of particular research questions, (2) identify specific mechanisms driving processes of interest, and (3) identify gaps in understanding. In the future, this framework can be used not only to facilitate our understanding of human–water systems but also to develop solutions to important water issues. Importantly, the iSAW framework is designed to be adapted to address water issues in other regions and natural resource domains beyond water.

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