Water Resources Research

Key Points:
- The foundation of sociohydrology are the many emergent phenomena that arise during the practice of water resources management
- Sociohydrology studies benefit from the concepts and methodologies drawn from a wide range of natural and social science disciplines
- Increased engagement with the broader water management communities and the development of common frameworks represent important issues for sociohydrology going forward

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Expanding the Scope and Foundation of Sociohydrology as the Science of Coupled Human-Water Systems

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Abstract Sociohydrology was launched as the science dealing with feedbacks between coupled human and water systems. Much of the early work in sociohydrology involved studies in spatially isolated domains (e.g., river basins) dealing with phenomena that involved emergent patterns in the time domain, with a focus on formulating and testing hypotheses about how they arise. The papers collected in this Special Section "Sociohydrology: Spatial and Temporal Dynamics of Coupled Human-Water Systems" illustrate that the scientific scope of sociohydrology has broadened over the last few years, with a rich diversity of phenomena studied and an expansion of the knowledge foundations and methodologies applied. These Special Section papers now incorporate methodologies and approaches from a wide range of social science disciplines, including anthropology, complex systems, economics, and sociology. The major themes tackled by these papers are understanding (i) water metabolism—the economic use of water; (ii) interactions between humans and droughts; (iii) interactions between humans and floods; and (iv) the role of human institutions, policy, and management. These collected papers provide a foundation for future research that strives to understand how to achieve water resources sustainability (society to water) and reduce the risk of hydrological hazards in society (water to society). Going forward, we suggest that the development of a common sociohydrology framework will be paramount for research development and student training. Additionally, increased engagement with the broader water management communities will enhance sociohydrology understanding and impact.

1. Introduction

The premise of sociohydrology is that our understanding of water systems is incomplete without the explicit inclusion of people (Srinivasan et al., 2016). Understanding and predicting processes in integrated human-water systems are challenging. This is because different disciplines, vocabularies, and perspectives must be synthesized (Troy et al., 2015; Wesselink et al., 2017; Xu et al., 2018). Bringing frameworks, theories, and models from different disciplines together is particularly challenging, as they typically operate at different scales (i.e., household vs. watershed), focus on different outcome variables (i.e., streamflow vs. welfare), and incorporate different scientific principles (i.e., mass balance vs. general equilibrium). Further, methods are grounded in different epistemologies and require distinct sets of prior knowledge for implementation. The papers collected in this Special Section contribute to this ongoing dialogue concerning the synthesis and a broadening of the scope of sociohydrology by showing how concepts and methods from different disciplines can be applied to study coupled human-water systems. In many respects, this is an exciting time for researchers involved in sociohydrology, as this movement toward consolidation and synthesis will likely open up more new avenues for thinking about and studying coupled human-water systems.

1.1. Sociohydrology to Date

Much of the early work on sociohydrology has involved studies in spatially isolated domains (e.g., river basins), focused on phenomena expressed in the form of emergent patterns in the time domain. The

analyses involved formulating and testing hypotheses on why these patterns arise. Examples include the levee effect as it applies to flooding in urban environments (Di Baldassarre et al., 2013) and the pendulum swing in water abstractions for human use in agriculture as opposed to water needed by the environment (Kandasamy et al., 2014; Liu et al., 2014). The adopted approach is to frame these systems in terms of system dynamics models involving coupled differential equations that depict the two-way feedbacks between human impacts on hydrology and hydrological impacts on human wellbeing (of some kind) and in this way are able to reproduce or reconstruct the observed emergent patterns. The key advance in these early modeling studies was the introduction of a social variable that reflected the mediating role played by human society in the two-way feedbacks. In the case of the levee effect, this was a social memory of floods (Di Baldassarre et al., 2015), and in the case of the pendulum swing, it took the form of environmental awareness (van Emmerik et al., 2014) or community sensitivity to the environment (Elshafei et al., 2014).

Subsequent work has helped to broaden the theoretical foundations of sociohydrology. For example, Sivapalan and Blöschl (2015) helped to frame sociohydrology in the context of co-evolution of human and water systems (in the time domain), with explicit inclusion (i.e., endogenization) of human agency in the form of changing human norms and values and more generally culture. They proposed a study approach of emergent phenomena based on narratives, causal loops, and the development and testing of models using available time series data. This opened the way for a diversity of studies organized by process sociohydrology, historical sociohydrology, and comparative sociohydrology. It was envisaged that a plurality of studies would thus be undertaken in a variety of contexts.

The early place-based studies (in the temporal domain) were also accompanied by several commentaries and critiques that sought to broaden the scope and foundations of sociohydrology. There was criticism that much of the early work was dominated by hydrologists, using mostly hydrological (or natural science) methods, and that sociohydrology can benefit from tools and methodologies found in socioecological systems and complex systems literatures (Blair & Buytaert, 2016; Troy et al., 2015). There were also critiques that warned that the field was moving toward theoretical studies divorced from real places involving real people. It was argued that instead of inferring the nature of human-water system feedbacks from historical (time series) data, these can also be obtained through field studies, through surveys, and other forms of data collection, with the goal of understanding human behaviors at a fundamental, empirical level (Mostert, 2018). There were calls for place-based studies in real places, with a greater involvement of social scientists in sociohydrological studies so as to expand the foundations of sociohydrology (Wesselink et al., 2016; Xu et al., 2018).

Human-water systems occur at multiple spatial scales and operate in time (Sivapalan et al., 2014). As such, sociohydrological phenomena arise not just in the time domain but they can also arise in the space domain or in space-time (Chen et al., 2016). Pande and Sivapalan (2017) argued that the endogenization of human agency in terms of changing human norms and values must be extended to space and to space-time, as demonstrated already by Chen et al. (2016), since this is an essential prerequisite for water sustainability. Along the same lines, Konar et al. (2016) made the case for a broadening of the scope of sociohydrology toward the regional and global scales. They argued that sociohydrology extended to the global scale can serve as the blueprint to track both water withdrawal and consumption (which may be different in a globalized world), which helps toward the assignment of responsibility for the stewardship of water resources and the advancement of global water sustainability.

The growth of the field of sociohydrology is also accompanied by calls for consolidation and synthesis that might lead to more general frameworks that would apply to a wide range of problems. This requires that sociohydrological studies be framed in the context of broad theoretical frameworks, such as water security and resilience. This would bring sociohydrology more aligned to and as a special case of older frameworks such as socioecological systems and thus benefit from the broad literature in coupled human-nature systems. The need for such generalization has long been felt, going all the way back to the very inception of the field (Srinivasan et al., 2012). There have been several recent commentaries proposing alternative frameworks to bring about such synthesis and generalization (Srinivasan et al., 2017; Lu et al., 2018; Sanderson, 2018).

2. Contributions of the Papers in the Special Section on Sociohydrology

The last 6 years have been a period of rapid growth of the field, partly in response to these commentaries and critiques. This special section brings together more than 30 papers that reflect significant advances in our

understanding of coupled human-water systems. In particular, they reflect a broadening of the scope of sociohydrology, not only in terms of the type of studies undertaken but also in terms of the disciplines involved. A wide range of methodologies is represented in this collection of papers, including the use of systems dynamics and agent-based models, multiple regression analyses, and field surveys. This indicates a certain broadening and maturing of sociohydrology, as also evidenced by a recent assessment of the co-authorship network in sociohydrology (Figure 1). In this section, we present a summary of the 31 papers appearing in this special section, organized under four categories: (i) water metabolism—the economic use of water; (ii) interactions between humans and droughts; (iii) interactions between humans and floods; and (iv) the role of human institutions, policy, and management. This is followed by perspectives on the way forward, guided by previous commentaries and conclusions drawn by the studies appearing in this Special Section.

2.1. The Water Metabolism (Use) of Humanity

Water is a key input to the economic production that underpins modern society (Marston et al., 2018). The papers in this special issue elucidate the important role that water plays in our society across a range of scales. At the smallest spatial scale, several papers evaluate the decision making of individual water users (Kuil et al., 2018; Mason et al., 2018). This grows in scale to papers that focus on urban water use (Chini et al., 2017; Worland et al., 2018) and to papers that explore water use at the national scale (Dadson et al., 2017; Dang & Konar, 2018). These papers highlight that the issue of scaling that has been the focus of much research in physical hydrology (e.g., Blöschl & Sivapalan, 1995) will continue to be an issue to consider in sociohydrology research. In addition to natural watershed boundaries, sociohydrology research must explicitly account for political boundaries.

Mason et al. (2018) examine how hydroclimatic variability impacts the decision making of water supply operators. They incorporate a concept from cognitive psychology—the "availability bias"—into their modeling framework. Model results compare well with synthetic reservoir operation data for flood control and water supply. Their model successfully captures the operator's preference selection across objectives and the dynamic evolution of extreme wet and dry situations.

Kuil et al. (2018) present a sociohydrological model that captures a farmer's crop choice and water allocation given his/her perception of water availability. They find that different farmer perceptions may lead to different crop patterns but also that similar, near-optimal crop patterns can emerge. The framework is consistent with the theory of bounded rationality, which assumes humans with limited cognitive abilities and imperfect information adopt satisficing behavior. The model by Kuil et al. (2018) also captures the rebound effect; that is, as crop water efficiencies improve, the newly available water will be reallocated on the farm instead of flowing downstream, since farmers will adjust their behavior to take advantage of the new water conditions.

Worland et al. (2018) explore the drivers of municipal water use in the United States. Their results indicate that the most important explanatory variables are average precipitation, number of people per household, partisan voting, water price, and regional price parity. However, they find that the environmental, economic, and social controls on water use are not uniform across the country. Counties in the Northeast and Northwest climate regions are more sensitive to social variables, whereas counties in the Southwest and East North Central climate regions are more sensitive to environmental variables. This statistical analysis helps us to understand the current drivers of water use in cities of the United States and make better predictions about future water use trajectories.

Chini et al. (2017) quantify the direct and indirect water use of urban areas in the United States. Their values could be used to inform future efforts to benchmark the use of energy and water resources in urban areas. In fact, they show that conservation opportunities exist for water and energy resources in both the direct and indirect supply chains of cities. Water embedded in the food supply chain of cities is the dominant indirect use of water and may represent a future opportunity to reduce the consumption water footprint of cities.

Dang and Konar (2018) show that trade leads to lower national water use. To do this, they employ causal inference methods to determine that trade does not impact the total or industrial water use of nations but that it does reduce the agricultural water use of nations. They find that trade openness reduces water use in agriculture primarily through the intensive margin or producing more crop value per unit of water.
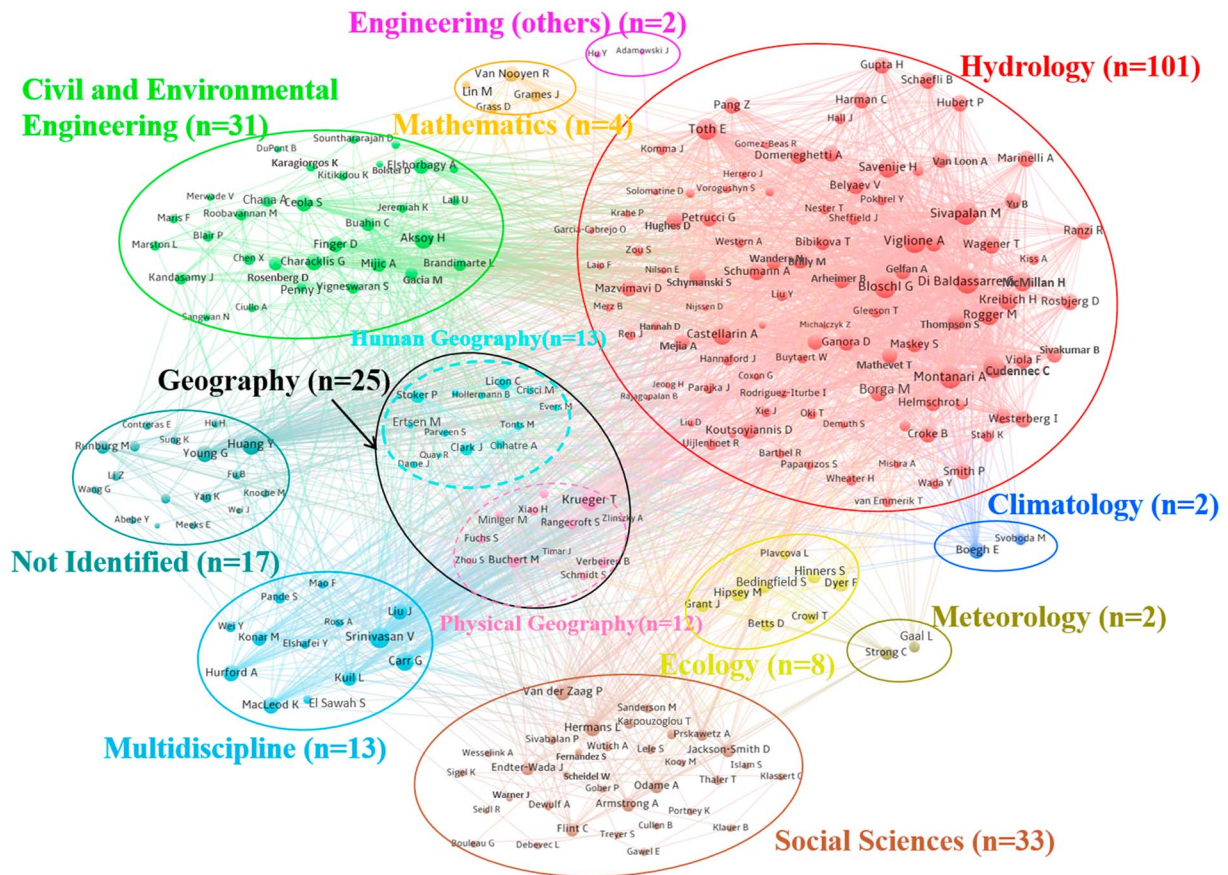
Figure 1. Co-authorship network grouped by disciplinary background. Figure reproduced with permission from Xu et al.

Dadson et al. (2017) develop a system dynamics model that combine both the productive and harmful roles of water in the economy. This model shows the link between national wealth, water-related productivity, and losses from water-related hazards. Wealthy countries with minimal water-related hazards likely will not need significant investment in water resources infrastructure. However, wealthy countries that face significant water-related hazards should probably expect to spend a significant fraction of national wealth on water infrastructure. Poor countries with poor water endowments and extreme hydrological variability are most likely to descend into a low-level equilibrium or poverty trap, the location of which is controlled by local social and environmental factors. Their conceptual modeling approach provides important insights for the design of robust policies for investment in water-related productive assets and risk management.

2.2. Interactions Between Water Use and Drought

Human activities from land use change and irrigation to dam building and water abstraction alter the propagation of drought through the hydrological cycle (Van Loon et al., 2016). In turn, drought impacts human activities, driving water conservation, shifting withdrawals from surface to groundwater, and prompting creative policy and infrastructure responses (Gonzales & Ajami, 2017; Gonzales et al., 2017; Marston & Konar, 2017; Nelson & Burchfield, 2017). The papers in this Special Section characterize and quantify both drought propagation and response and the influence of climatic and social factors in shaping these processes.

Apurv et al. (2017) assess the role of climate characteristics in drought propagation and the interactions of these processes with drought response. They test the impact of seasonality, the phase shift between precipitation and evaporation cycles, and aridity on the relationships between meteorological drought, hydrological drought, and groundwater drought. They find that the relative differences in meteorological and hydrological drought are explained by climate aridity and the timing of precipitation relative to potential
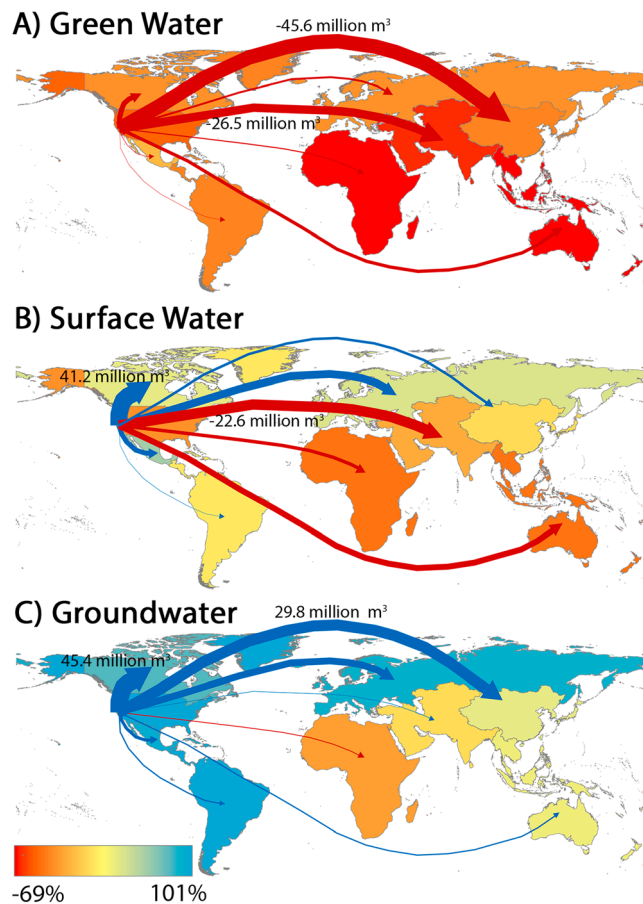
Figure 2. Percent change in virtual water transfers from the Central Valley of California to the rest of the world over the course of the 2011–2014 drought. Maps indicate the percent change in (a) green, (b) surface, and (c) groundwater virtual water transfers. Arrows show the change in the volume of virtual water transfers (m³) and are scaled relative to size. Volumes are provided for the largest links. Red arrows indicate a reduction in virtual water transfers; blue arrows signify an increase. Figure reproduced with permission from Marston and Konar (2017).

evapotranspiration and that low interannual precipitation variability is associated with greater risk of drought resulting in groundwater depletion (Apurv et al., 2017).

While Apurv et al. (2017) assess the climatic controls on drought propagation, Nelson and Burchfield (2017), Marston and Konar (2017), Gunda et al. (2018), and O'Keeffe et al. (2018) evaluate the influence of social factors in agricultural systems during drought. Both Nelson and Burchfield (2017) and Marston and Konar (2017) investigate responses to the 2012–2014 drought in California's Central Valley. Nelson and Burchfield (2017) developed a spatiotemporal Bayesian model to assess the effect of water rights structures on agricultural production during drought. They find that watersheds with more senior water rights are associated with higher productivity during drought but that while junior water rights are more likely to fallow, their production is less sensitive to drought. This indicates that junior water rights holders have adapted to periodic reductions in surface water. One way they have adapted is groundwater well construction, confirmed by the work of Marston and Konar (2017). Marston and Konar (2017) investigate how the California drought's agricultural impacts propagated through the global food trade system (see Figure 2). They found that while harvested area was reduced (due to fallowing), the water footprint grew due to rising temperatures and cropping changes. The reduction of harvested area led to reduced food commodity trade from the Central Valley. Surface water transfers also fell during this period, but groundwater transfers nearly doubled, strengthening the relationship between food trade and groundwater depletion.

Gunda et al. (2018) and O'Keeffe et al. (2018) also focus on agricultural systems, investigating water stress response dynamics of an acequia community in New Mexico and farmers in Uttar Pradesh, India. Gunda et al. (2018) couple an acequia model, developed by Turner et al. (2016), to a hydrological model to assess the impact of upstream hydrological changes and downstream demand changes on crop production and migration. A unique feature of their study is that they evaluated the role of mutualism in sustaining the acequia during drought. They model mutualism as a function of community participation, which is in turn shaped by employment effects, parcel size, fallow land percentage, and the addition of newcomers to the community. They find that adaptive measures such as shifting crop selection allows the community to adapt to reductions in streamflow but that downstream pressures to reduce water use lead to decreased agricultural profitability. Parallel to the articles in this issue on flood dynamics (Leong, 2018; Sung et al., 2018; Yu et al., 2017), Gunda et al. (2018) demonstrate the importance of community dynamics in influencing community drought response behavior. O'Keeffe et al. (2018) presents the development, in a bottom-up manner, of a coupled sociohydrological model that captures observed farmer irrigation practices in the State of Uttar Pradesh, India, including two-way feedbacks between environment and farmer behavior. In particular, by including these feedbacks between the behavior of water users, irrigation officials, and agricultural practices, the work highlighted the importance of directly including water user behavior in policy making and operational tools to achieve water and livelihood security.

Gonzales and Ajami (2017), Gonzales et al. (2017), and Breyer et al. (2018), in turn, investigate drought responses in urban areas. Gonzales and Ajami (2017) adapt a water demand model from Garcia et al. (2016) to assess the impact of changing scarcity awareness on water demand in three San Francisco area water utilities. The three utilities selected differ by average income, percent residential, and average per capita water use. They find that these socioeconomic factors help explain differences in drought response and postdrought rebound. Similarly, Gonzales et al. (2017) observe that the ease and cost of conservation may vary significantly. This motivates them to introduce a water conservation trading scheme and apply

the scheme to utility members of the Bay Area Water Supply and Conservation Agency in California. Under conservation trading, utilities that do not meet their targets may purchase credits, and utilities that exceed targets sell credits in an auction. Gonzales et al. (2017) find that trading can reduce the costs of conservation by 20% and that coordinate decision-making increases the benefits for the utilities. Breyer et al. (2018) ask how water conservation impacts urban hydrological cycle in a study of Austin, Texas. They use multiscalar statistical analysis to demonstrate that the outdoor water conservation policies can cascade upward to the watershed scale or downward to the submunicipal scale. Together these studies highlight the importance of considering both feedbacks from drought to human action and from human response to hydrological cycle.

2.3. Interactions Between Human Actions and Floods

An important research topic for human-flood interaction is how human behavior and cultural traits evolve in response to flood events and how the resulting social change leads to shifts in hydrologic components that either mitigate or exacerbate floods (Loucks, 2015). Of special interest is understanding the feedback mechanisms that might explain emergent phenomena arising from human-flood interaction, for example, the levee and adaptation effects (Merz et al., 2015). An influential work in this direction is that of Di Baldassarre et al. (2013). Using a system dynamics model, the authors propose feedback mechanisms that can generate the qualitative patterns of levee and adaptation effects. This work has stimulated much interest and discussions in the field. One salient issue in these discussions is how to model the response of social system to the physical process of flooding. The papers in this theme focus on this linkage to provide alternative and complementary views to the approach used by Di Baldassarre et al. (2013, 2015).

Yu et al. (2017) presents a system dynamics model of how an agricultural community mobilizes collective action for levee repair in the face of hydroclimate variability and nonfarm job opportunities. An important concept from the field of political economy is introduced in this work—institutional arrangements (rules and norms) for governing people's collective action (e.g., Ostrom, 1990). Institutional arrangements, which are rules and norms that humans devise to govern their behavior, can play a critical role in reducing uncertainty in complex, uncertain situations (North, 1990). Inclusion of institutional arrangements into sociohydrology modeling helps to unpack underlying processes of social response into (1) rules and norms, (2) behavioral choice toward such institutional arrangements (e.g., abide vs. oppose), and (3) situational factors that influence the decision making (e.g., social memory).

Sung et al. (2018) explores how different societal policies on flood control influence long-term trajectories of human-flood interaction. The model by Di Baldassarre et al. (2013) considered only two policies from a myriad of possible ones: green society (no structural flood control) and technological society (raising of levees whenever flooding occurs). Sung et al. (2018) go beyond these two control policies by exploring the effects of several adaptive policies on community maintenance of levees. In doing this, Sung et al. (2018) apply control theory from engineering to conceptualize how a human society learns from flood events and adjusts its flood control policies (Figure 3). The same application was made in the field of social-ecological systems to analyze how a farmer-managed irrigation system dynamically adapts its water distribution and cost-sharing rules through learning by doing (Yu et al., 2016).

Leong (2018) in this special section provides a more nuanced perspective on the levee and adaptation effects. The author goes beyond the dichotomous view of these two phenomena by arguing that (1) a heavy dependence on structural flood protection measures may not always lead to the levee effect and that (2) little use of structural measures and frequent exposure to flooding may not always lead to the adaptation effect. Leong (2018) exposes these possibilities by collecting and analyzing the narratives of people in several floodplain villages of India.

Girons Lopez et al. (2017) and Du et al. (2017) focus on flood warning and evacuation behavior of people. Girons Lopez et al. (2017) developed a conceptual model to examine how the efficiency of flood warning is influenced by social preparedness, which is defined as the knowledge and capacities of a social system to proactively respond to a disaster (United Nations International Strategy for Disaster Reduction, 2009). This work uses social memory of flood risk as a proxy for social preparedness. The model results show that a high social preparedness can affect the efficiency of flood warning system; that is, even if the warning
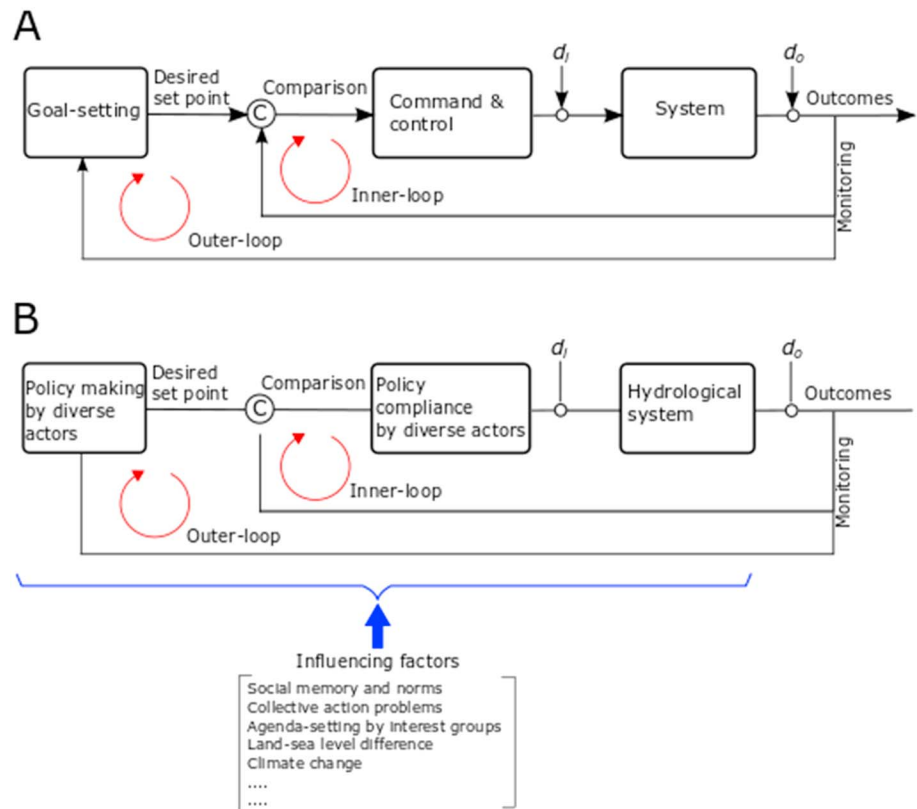
Figure 3. A generic block diagram control system theory (a) is applied to conceptualize a human-flood system governed by adaptive flood control policy (b). The symbols d_i and d_o represent internal problems and external forcing, respectively. The circle C represents comparison between the current system state (current flood protection level) and desired set point (target flood protection level) for computing the error value. Inner-loop process involves control activities that are done to minimize the error. Outer-loop process involves updating of the desired set point. Situational factors such as social memory, community attributes, and climate change can influence the dynamics of such inner- and outer-loop processes in human-flood systems. Adapted from Sung et al. (2018) and Yu et al. (2016).

system is inaccurate and the traffic network is congested, a high level of social preparedness can compensate for these weaknesses and mitigate flood-related losses.

Du et al. (2017) developed an agent-based model to understand the coupled dynamics of public opinion and flood evacuation processes and how these dynamics are influenced by multiple information sources (global casting of flooding, social media, and observation of neighbors) and transportation system states. A key distinction of this work is reflecting the fact that individuals' evacuation behavior is not only influenced by the flood warnings from emergency managers but also by peer-to-peer communication through social media and observation of neighbors' behavior. The model results show that social media can make evacuation processes more sensitive to changes in flood warning and neighborhood observation.

Thompson et al. (2017) in this special section focuses on the link from human modifications of water resources to the physical process of flooding. This work uses a theoretical approach to investigate how the development lowlands affects the flooding of lowland environments and water balance partitioning. The model results show that modifications such as building levees and changing land cover can generate trade-offs among flood occurrence, flood duration, and total evaporation.

Finally, MacVean et al. (2018) extended the work of Thompson et al. (2017) to reconstruct the hydrology of the 1850–1920 period for California's Central Valley by synthesizing newly reconstructed time series of precipitation, basin inflows, land use change, and levee construction, using a parsimonious and semidistributed version of the model presented earlier by Thompson et al. (2017). Within the limitations of the reconstructed time series, their detailed analyses with the use of the model suggested that levee construction, rather than

land-use change, had the greatest impact on the hydrology and that the decreases in annual delta outflows accelerated after 1920.

2.4. Human Institutions, Policy, and Management of Water

Water management is the point at which human systems and water systems intersect, blurring the line between "human/social" systems and "natural" systems. The papers in this theme draw upon sociohydrological frameworks to provide insights into the institutions and decision-making processes that co-evolve with water system process to mutually shape water management. Water management may be informed by models, and traditionally, the focus of these models has been hydrological dynamics. Of growing importance, however, is how to more rigorously incorporate the human element into management of sociohydrological systems.

Massuel et al. (2018) argue that traditional approaches to hydrology must become more open, and sensitive, to the human sciences. The social dynamics of human systems should be conceptualized as rigorously as the hydrological dynamics, but crucially, they contend that this will involve taking much more seriously the context-specificity of human systems. Their analysis of the Wadi Merguelil watershed and the downstream Kairouan Plain in central Tunisia shows that a conventional water budget modeling framework was not able to account for the many social factors that influence irrigation withdrawals. Instead, an approach recognizing the key role of cultural values allows researchers to better grasp the qualitative aspects of how humans interpret and make sense of sociohydrological systems. Their approach is skeptical of generalizable knowledge because of the site-specific dynamics that emerge from local interactions and that are contingent upon local cultural values.

Because generalization continues to be a goal in sociohydrology, there is a real need to develop empirical frameworks that span time and space, while recognizing the context-specificity of human systems. Sanderson et al. (2017) take a step in this direction. Situated at the individual level, this paper develops a social-psychological model to explain policy choices among citizens in a semiarid agricultural region in the Central U.S. Great Plains. Here, again, values are important. Their analysis reveals how cultural values underlie belief formation and normative support for water management. Their model allows comparisons of culture-based decision-making processes among both farming and nonfarming populations in the watershed. These explicit comparisons enable researchers to identify areas of potential value-based conflict and consensus in water management.

Another social aspect receiving greater attention recently is that of social position or, more broadly, the degree of stratification in a social system (Sanderson, 2018). Haeffner et al. (2018) explicitly investigate this question in the northern region of Utah, USA. Using a mixed methods approach involving interviews and surveys, they find that city leaders and the public differ in their concerns about water issues: leaders were more concerned about water infrastructure, and the public was more concerned with water availability and financial costs. Especially noteworthy is the finding that perceptions of water quantity and quantity are not merely shaped by the built structures and natural systems but instead are mediated by social structures—values, norms, beliefs, gender roles, and occupational structures.

William et al. (2017) lend further support for the proposition that social position matters for modeling the human component of sociohydrological systems. This paper uses cooperative game theory to evaluate storm-water management approaches in the Gwynn Falls watershed, a highly urbanized watershed in West Baltimore, MD, USA. Among the key findings is that municipal-level regulation results in the largest reductions in pollutant loadings, but, again, context matters. The effectiveness of a regulatory approach depends on many socially contingent factors such as political, financial, and again, the distribution of actors' positions within spatial stormwater networks.

Taking the context seriously means considering it as an issue related to the scale of sociohydrological systems. Schifman et al. (2017) propose a framework for sociohydrology that attempts to enhance the adaptability of these systems by optimizing multiple functions and outcomes, including ecosystem services, spanning various institutional scales. They apply the framework to green infrastructure initiatives in Cleveland, OH, USA and Atlanta, GA, USA. The results demonstrate the model's potential utility beyond these cases, while avoiding the pitfalls of a one-size-fits-all approach. Along these lines, Voisin et al. (2017) integrate a regional integrated assessment model with an Earth system model to better understand

the effects of sectoral human actions on spatial patterns in water resources, focusing especially on feedbacks between the human and natural systems. The impacts of water management depend on scale, and sectoral human actions influencing groundwater use and water use recycling shape spatial patterns in streamflows and water deficits.

Roobavannan et al. (2017) incorporate several of the key elements discussed under this theme. This paper assesses the pendulum swing hypothesis in the Murrumbidgee River Basin in east Australia. Economic diversification emerges as the key variable, reshaping cultural values and norms over time and shifting the balance of preferences away from agricultural production and economic growth toward environmental restoration and sustainability. The paper sheds light on how scale, social structure, cultural values, and water resources interact over time, co-evolving through feedbacks to generate emergent outcomes.

Wescoat et al. (2018) use historical geographic and statistical methods to gain context-specific understanding of how and why measurements of water flows have been done in the ways they have in the Indus River Basin of Pakistan. They do their analysis in three levels of water channels: basin, canal, and local distributary levels. The paper demonstrates that the combined use of historical geographic and statistical methods can be a viable approach for conducting sociohydrology research.

Treuer et al. (2017) in this special section provides a rich context specific analysis of how urban water utilities can transition toward more sustainable water management practices. Using a case of Miami-Dade County, Florida, they demonstrate that a better understanding of such a transition requires a data-narrative approach that systematically synthesizes quantitative and qualitative data sources, including local knowledge of practitioners and archived documents. Their analysis shows that the alignment of certain biophysical, regulatory, financial, and political conditions likely have contributed to the region's transition toward improved water sustainability. One unique aspect of the study is the use of institutional analysis (analysis of rules and norms) based on government documents to understand regulatory factors influencing such a transition.

Finally, Bijl et al. (2018) presented a model for freshwater scarcity assessment that integrated the impacts of future population growth, agricultural production patterns, energy use, economic development, and climate change on the global freshwater cycle. With such integration between hydrology and economy, the model was able to generate greater understanding of the competition dynamics between the different freshwater users and different allocation mechanisms, at the basin and grid scales. In this way, the application of the model enabled broad conclusions to be made about the effects of climate change and variability and water use efficiency improvements in irrigated agriculture on global water withdrawals and deficits.

3. Going Forward

The papers in this Special Section employ diverse disciplinary perspectives and methods to advance our understanding of coupled human-water systems. In so doing, they have also contributed to a broadening of the scope and foundations of sociohydrology. However, a few major threads of research remain for the future. Our review of the papers suggests the following questions yet to be addressed: (1) How will people adapt to future water scarcity? (2) How can we better anticipate the hydrological impacts of human activity across scales? (3) What policies or infrastructure investment can best protect communities from flooding and drought? (4) What policies can promote water security and when is unsustainable water use "ok"? (5) How does the socioecological context shape the success or failure of these policies? These questions will be increasingly important to address in our era of global change. Challenges also remain in connecting sociohydrological science to practice, developing generalizable knowledge of coupled human water systems, and training the next generation of practitioners and scholars.

3.1. Connecting Sociohydrology With Practice

Increasingly, it will be important for sociohydrology to engage with the broad community of water resources managers. One avenue to potentially accomplish this goal is by explicitly evaluating the uncertainty and sensitivity inherent in the modeling of the sociohydrology system of interest. As in any model, the relevant variables and mechanisms included depend on the research question and scope of the problem. Recent sociohydrology work aims to make all relevant sources of uncertainty explicit in a structured way (Westerberg et al., 2017). This assessment of uncertainty in system outcomes can help to structure

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dialogue with water resources managers and planners, as well as engage them in the development and process of the research (Westerberg et al., 2017). However, we also recognize that the nature of sociohydrological systems implies a different split between epistemological and aleatory uncertainties than pristine hydrological systems (Srinivasan et al., 2016). Engaging stakeholders in model development through structured dialogue, communication, and understanding about system uncertainty strengthens the research aspects of the model and also better integrates interdisciplinary communities and research with practice (Wesselink et al., 2017). While traditional hydrology or water resources management make predictions of future events based on past observations, sociohydrology addresses the prediction of novel phenomena to understand system dynamics and limits (Levy et al., 2016). Methodologies to account for uncertainty in sociohydrology should respond to the nature of prediction in sociohydrology (Srinivasan et al., 2016), and therefore, uncertainty assessments should focus on the evaluation of model structural adequacy and the ability to reproduce observed patterns and signatures.

Sociohydrology and water resources system science are similar in that they consider both water and people and their mutual importance. The key distinction is that while water resources management focuses on how water resources can be better managed to benefit both society and nature by using multidisciplinary and participatory approaches (Kasprzyk et al., 2018), sociohydrology focuses on the complexity and emergent outcomes of human and water interactions (Sivapalan et al., 2012). Water resources management based on the assumptions of static human and water components (thus, insufficient recognition of the complex and adaptive nature of coupled human and water systems) can fail to deliver desired management goals (Vogel et al., 2015). Indeed, many of the phenomena that have been the subject of analysis in sociohydrology, and reviewed here, have arisen in the normal course of water resource management, as failures or unintended consequences (Gohari et al., 2013), due to some long-term feedbacks between humans and water systems not being fully accounted for. Thus, introducing and applying sociohydrology insights into water resources management can potentially be very useful. Similarly, insights from water resources professionals can help research to identify system constraints (in modeling) and real-world problems to tackle, making the research more impactful. This calls for more engagement between the sociohydrology and water resource management communities than has been demonstrated thus far.

A parallel has, in fact, occurred in the fields of natural resource management and social-ecological systems research. Realization of the complexity and nonlinearity of interactions between social systems and natural systems that sustain them has challenged conventional natural resource management worldwide and led to the widespread acceptance of the concept of the social-ecological system into the field of natural resource management (Folke, 2006). As sociohydrology rapidly expands in the next few years, we expect to see a similar convergence to take shape between sociohydrology and the field of water resources management. Improvement of water management practices through a broadening to include multiple social, economic, and cultural perspectives, assisted by sociohydrology, takes on added importance in the context of the United Nations Sustainable Development Goals (United Nations, 2018).

3.2. Developing Generalizable Knowledge of Coupled Human Water Systems

Going forward, it is likely that sociohydrology will interface with other nexus issues. Water is at the heart of many grand challenges for society, making it likely that water resources researchers may contribute to the intersection of water and food security, economics, energy, and/or biodiversity (Bierkens, 2015). In fact, a growing number of large-scale hydrologic models have incorporated human impacts on the hydrological cycle in recent decades (Wada et al., 2017). Yet the representation of human activities in hydrological models remains challenging and may prove to be a key opportunity for sociohydrology engagement. Questions also remain as to what features make sociohydrology unique compared to other interdisciplinary approaches and what sociohydrology might learn from these other approaches and vice versa.

Further, challenges and opportunities remain in the development of common frameworks and general theories for sociohydrology. Frameworks usually specify a general set of variables, and relationships among them, that a researcher should consider when analyzing a case. A key benefit of a common sociohydrology framework would be that it will allow a structured and consistent comparative analysis of diverse case studies across contexts, thereby facilitating the discovery of generalizable patterns. A general sociohydrology theory can provide generalizable understanding of such patterns by clarifying how different case studies relate to one another in terms of causal processes, especially multilevel and multiscale processes

associated with a sociohydrological phenomenon. Although most sociohydrology studies are already based on established theories that explain particular processes (e.g., rainfall runoff and expected utility theory), general theories that provide insights into common system-level aspects and multilevel and multiscale dynamics across different place-based studies are relatively scarce and should be pursued in the future as the field matures. Nevertheless, the papers in this Special Section take some initial steps in this direction. For example, Dadson et al. (2017) present a framework that connects water use and risk into an economics framework. Kuil et al. (2018) applied the theory of bounded rationality to analyze farmer crop choice and water allocation decision making, and Treuer et al. (2017) applied Triple Exposure Theory in their assessment of transitions to sustainable water management. Further, papers (Roobavannan et al., 2017; Yu et al., 2017) in this Special Section test and refine existing hypotheses such as the levee effect and the pendulum swing, contributing to theory development.

Early sociohydrology studies focused on system dynamics modeling as the primary methodology. The papers in this Special Section highlight the breadth of methods that can be applied to address sociohydrological questions. Leong (2018) collects stakeholder narratives to illustrate how cases can illustrate aspects of both the levee effect and adaptation effect. Treuer et al. (2016) construct narratives and pair them with quantitative metrics to enable cross case comparison without losing the nuance of case context. Identifying feedback relationships across temporal and spatial scales is key to advancing sociohydrology (Thompson et al., 2013). The complex, hierarchical and co-evolutionary nature of sociohydrological problems requires careful selection and interpretation of data analysis methods. For example, while correlation-based methods (e.g., OLS regression, granger causality, and Bayesian inference) can identify linear couplings and their timescales, they cannot unambiguously identify the direction when relationships are asymmetric (Ruddell & Kumar, 2009). In this issue, the authors apply a range of statistical methods such as structural equation modeling (Breyer et al., 2018), hierarchical Bayesian modeling (Nelson & Burchfield, 2017), and regression with instrumental variables (Dang & Konar, 2018) to address these challenges. While Gunda et al. (2018), Dadson et al. (2017), Sung et al. (2018), and others continue the tradition of applying system dynamics modeling to gain qualitative understanding of system behavior, they advance this approach through their application of human system dynamics. One critique of system dynamics approach in sociohydrology is that the diversity of actors is not accounted for. Du et al. (2017) address this challenge by developing an agent-based model of flood warning and evacuation behavior. Collectively, the articles in this issue demonstrate the potential to synthesize multiple methods to increase the robustness of sociohydrological findings—critical to applying insights in practice.

However, to address societal challenges, scientific findings must be salient as well as robust. Codevelopment of research aims and coproduction of research products can be an effective way to increase research salience but also introduce new challenges (Tidwell & Van Den Brink, 2008; MacKenzie et al., 2012). Multiple papers in this special issue solicit stakeholder input as data or use stakeholder feedback to refine analyses (e.g., Gunda et al., 2018; Leong, 2018; Treuer et al., 2017). While past sociohydrology work has addressed knowledge transfer (e.g., Gober et al., 2014), no papers in this issue focus on knowledge transfer or research codevelopment, and more work remains to ensure that research efforts in sociohydrology can be applied in practice. Additionally, proper characterization of the uncertainties and sensitivities that exist in sociohydrology models must be explored to inform stakeholders. In this way, policymakers can be engaged to manage uncertainty—rather than reduce it—in a sociohydrology system (Gober et al., 2017).

3.3. Training the Next Generation of Practitioners and Scholars

Future education and training of scholars and practitioners equipped to tackle outstanding questions in this field will be critical. A key question for the field is to determine if the training of researchers should shift or broaden to tackle sociohydrological challenges or if the training should emphasize teamwork and communication skills to facilitate interdisciplinary collaboration. Another key question is the relationship between sociohydrology and water resource managers. As sociohydrology is an emerging science, it will engage more directly with water managers—as stakeholders, along with the general public—as it develops. Indeed, these interactions will be necessary in order to incorporate insights from managers and "ground truth" sociohydrological models.

Tackling sociohydrological challenges will require knowledge of water resources science as well as the social sciences, with the precise skill sets varying by the scientific questions pursued. A key question for mentors

and advisers is to what degree individual researchers should be trained in this skill set versus preparing researchers to collaborate across disciplines. However, a core body of knowledge will remain essential so that scholars can interface and communicate with one other easily. Programs of study will grapple with what this fundamental body of knowledge is and should be. We suggest that several strategic skills to develop include methods in data science, complex systems science, coupled human and natural systems modeling, and causal inference. Going forward, science communication training will be an increasingly important skill set to develop, since this will enable work across disciplines, with policymakers, water managers, and the broader public.

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