Developing a sustainability science approach for water systems

Article:

Dumas, Marion and Rising, James (2020) Developing a sustainability science approach for water systems. Ecology and Society. ISSN 1708-3087 (In Press)

Insight

Developing a sustainability science approach for water systems

Version: 2 Submitted: 2020-04-03

ABSTRACT

We convened a workshop to enable scientists who study water systems from both social science and physical science perspectives to develop a shared language. This shared language is necessary to bridge a divide between these disciplines' different conceptual frameworks. As a result of this workshop, we argue that we should view socio-hydrological systems as structurally co-constituted of social, engineered, and natural elements and study the "characteristic management challenges" that emerge from this structure and recur across time, space and socio-economic contexts. This is in contrast to theories that view these systems as separately conceptualized natural and social domains connected by bi-directional feedbacks, as is prevalent in much of the water systems research arising from the physical sciences. A focus on emergent characteristic management challenges encourages us to go beyond searching for evidence of feedbacks and instead ask questions such as: What types of innovations have successfully been used to address these challenges? What structural components of the system affect its resilience to hydrological events and through what mechanisms? Are there differences between successful and unsuccessful strategies to solve one of the characteristic management challenges? If so, how is this affected by institutional structure, and ecological and economic context? To answer these questions, social processes must now take center stage in the study and practice of water management. We also argue that water systems are an important class of coupled systems with relevance for sustainability science because they are particularly amenable to the kinds of systematic comparisons that allow knowledge to accumulate. Indeed, the characteristic management challenges we identify are few in number and recur over most of human history and most geographical locations. This recurrence should allow us to accumulate knowledge to answer the above questions by studying the long historical record of institutional innovations to manage water systems.

Key words: water systems, socio-hydrology, institutions

INTRODUCTION

Water has always been, simultaneously, one of humanity's most fundamental resources and a potential threat. Indeed, water's natural spatio-temporal variability has made it a constraint on economic activity, posed threats to capital assets, and provided pathways for disease since sedentary settlements first appeared. Water is fundamental to the organization of human societies because most human uses of water require collective management. The resulting interactions among the social, engineered, and natural aspects of water systems generate challenges around managing flood risk, drought consequences, and water quality. We note that these challenges have consistent characteristics across diverse social, economic, and technical contexts, and so we call them 'characteristic water management challenges'. These challenges have been drivers of innovation in water institutions through millennia of human history. We argue that their recurrence and the multiplicity of institutional innovations that arose to address them over long historical time reveal general patterns of coupled social and hydrological system dynamics. Studying these patterns leads to a research program that can accumulate knowledge across cases and enhance our understanding of the institutional innovation needed to adapt to an uncertain future - both for water problems and sustainability problems more generally.

Interdisciplinary research in water systems has frequently used approaches from hydrology and engineering, combined with approaches from economics and other behavioral sciences. It hasn't often capitalized on strategies that take a broader institutional lens, such as from the Socio-Ecological Systems (SES) literature or political science. On the other hand, some aspects of water system research, particularly its long history of recognizing the deep coupling between hydrological states and collective social behavior, can also generate useful strategies for SES research. We believe that looking for regular patterns in institutional behavior and how these patterns recur in different contexts can contribute to a more generalizable understanding of sociohydrological systems.

MOTIVATION AND METHODS

This Insight paper is a synthesis of ideas that arose from an interdisciplinary workshop entitled "Modeling and Measuring Socio-Hydrological Dynamics Across Scales", held at the Santa Fe Institute in June 2018. The motivation for holding this workshop was to develop a more integrated understanding of how social, institutional, and economic activities influence water outcomes: both human and environmental. These outcomes include both how productively, fairly and sustainably water is used, and the consequence of those choices on hydrological outcomes such as flood risk, groundwater depletion, or water quality. Authors Brelsford and Dumas saw a great difference in framework and language between the social science literature (including from socio-ecological systems) and the literature on water systems and water resources, developed by hydrologists, on the other. The water systems literature has made great strides in incorporating human factors in its analyses (e.g. Davies and Simonovic, 2011). However, it uses a restricted view of human agency, in the form of fairly deterministic rules for the dynamics of population-level variables or for individual-level behaviors (e.g., Elshafei et al., 2014; Gohari et al., 2017), or focusing on decision-theoretic frameworks for management (Merz et al., 2015). It does not typically integrate institutions and collective decision-making (with the important exception of the subfield of water conflict, which makes use of game theory to analyze conflicts, e.g. Madani et al., 2014). The social science literatures related to water, on the other hand, tend to describe in great detail the social arrangements developed to manage water on a case by case basis (e.g., Heikkila et al. 2011, Lubell et al. 2014), but with little systematic and deep connection to the hydrological outcomes deemed important by hydrologists and water managers.

We organized the workshop to explore this gap and attempt to build a common set of questions between fields concerned with water systems. Workshop attendees were roughly equally distributed between the social sciences and natural sciences (including political science, economics, sociology, anthropology, hydrology and engineering). The workshop's 23 attendees were gender-balanced, came from 5 continents and ranged from graduate student to senior scientist, all with research that focuses on water systems. Workshop time was balanced between informal, small-group discussion of early-stage research ideas, and plenary sessions focused on identifying shared research goals across the various intellectual communities represented. The plenary sessions explored drivers of water supply, demand and allocation conflicts on different temporal and spatial scales. In the informal sessions, researchers worked in small groups, contributing ideas to each other's existing research in light of the important questions identified in the plenary sessions. Methodological opportunities and challenges identified in the informal sessions also fed back in plenary sessions explicitly focused on methodological and empirical questions.

The diversity of backgrounds and approaches represented at the workshop allowed us to extract shared ideas that we think can help unify and move the study of water systems forward. As detailed in the rest of the paper, one of our main conclusions is that we can integrate institutions into hydrological modeling by asking different questions of the modeling effort and by identifying recurring patterns. We think that this reorientation may help socio-hydrology move away from predicting long-term dynamics and instead work toward analyzing how hydrological, economic and institutional factors interact to affect the resilience and adaptability of the system. Within the social sciences, a focus on recurrent management problems can help better accumulate knowledge across cases.

CHARACTERISTIC WATER MANAGEMENT PROBLEMS

Over recent decades, researchers have sought quantitative theories to describe the behavior of coupled human and physical systems (Anderies et al., 2004; Holling, 1973; Liu et al., 2007; Olsson & Jerneck, 2018). This literature notes that inherent features, such as non-linearity, inter- and intra-dependencies, non-stationarity, hysteresis, and multiple objectives, call for strategies to describe and predict these system behaviors that are distinct from the empirical strategies used successfully to explore natural and ecological systems independent of human activities. Despite substantial effort (Anderies, 2015; Preiser et al., 2018; Schlüter et al., 2019), quantitative frameworks that describe the behavior of coupled human and physical systems are still limited. We propose that seeking generality across management challenges (as done for example in Srinivasan et al., 2012), rather than across modeling problems will help advance sustainability science and policy.

What do we mean by generality across management challenges? We claim here that water problems in different places and different times resemble each other, and that this resemblance should allow us to gain generalizable knowledge about socio-hydrological systems' behaviors and management strategies. For example, where water scarcity is a threat, the characteristic management challenges generally concern allocation and the long-term (im)balance of supply and demand. Successful management generally centers around the allocation of water rights or access to water across people, economic sectors, and ecological uses (Coman, 2011, Brewer et al., 2006). Sustainable water management also calls for addressing the inter-temporal and spatial dynamics of water consumption in relation to reservoir or groundwater depletion (Fishman et al., 2011). When too much water is a threat, institutional challenges generally concern the distribution of flood risk and water damage across space and social groups. Impacts are influenced by flood mitigation, coastal protection, and various forms of green infrastructure. Choices and policies about the physical location of human activities affect the distribution and impact of risk across social groups, economic sectors, and ecosystems (Di Baldassarre, et al., 2018; Li et al., 2016; Quinn et al., 2018). Water quality can be impaired by biological (e.g. pathogens), geochemical (e.g. nutrients or pollutants) and thermal (e.g. heat release) disturbances. When water quality is a problem, an important institutional challenge is how to manage the deep causal uncertainty and ignorance about the cumulative impacts of these disturbances, which tend to interact in complex ways and amplify over time (Beck, 1987;

Polasky et al., 2011; Hering et al., 2015). Further challenges include the allocation of pollutant loads and the monitoring, and enforcement of these allocations given the diffuse nature of non-point source pollution (Scholz & Wang, 2006; Xepapadeas, 2011).

A research program focused on water management challenges stands a better chance to deeply integrate knowledge from different disciplines. It can also organize research so as to successfully accumulate knowledge, thanks to the re-occurrence of these challenges in space and over a long stretch of history, making it possible to draw systematic comparisons. In contrast, focusing on modeling problems tends to lead to more siloed research streams that ignore important dimensions of the system. For example, the current socio-hydrology literature models human-behavior in the framework of differential equations. This implicitly leads scientists to model average behavior, leaving out heterogeneity in individual behavior as well as collective decisions and institutions. As another example, much work in political science and public policy focuses on modeling and measuring cooperative behavior without necessarily having a clear representation of the water problem to be solved.

FIGURE 1 about here.

GENERAL LESSONS FROM HISTORICAL INSTITUTIONAL INNOVATIONS

The study of both modern and historical coupled social and hydrological systems yields a wealth of strategies, some successful, to address these characteristic problems. Ancient water managers developed institutions and technologies capable of robustly coping with semi-arid and highly variable climatic conditions (Nelson et al., 2010). They developed solutions to co-occurring problems, including complementary arrangements to govern water withdrawals and the provisioning of water infrastructure (Ostrom, 1993), or fine-tuned patterns of cropping that simultaneously address water needs and other ecological variables (Lansing et al., 2017). Historical studies also inform us on rates of adaptation to the changing availability of water (Hornbeck & Keskin, 2014), as well as constraints to adaptation in the absence of storage infrastructure (Brown & Lall, 2006). The historical record offers fantastic examples of how institutions are shaped by environmental conditions, for example the gradient of water institutions from the humid American East to the dry American West (Libecap, 2011), or the resilience of pastoral communities to the variable ecological conditions of dryland environments (Boone, 2014). These examples of historical institutional and socio-technical innovations demonstrate the broad range of strategies and sociotechnical transition pathways that are observed when socio-hydrological systems respond to shocks and disruptive change (Geels & Schot, 2007). Crucially, an emerging research agenda addresses the mechanisms by which humans sometimes succeed and sometimes fail to modify institutions as water availability or patterns of water usage change (Garrick et al., 2013; Elshafei et al., 2014; Sivapalan & Blöschl, 2015).

Despite millennia of human experiments, the management of coupled social and hydrological systems is in need of innovation from practitioners and scientists. Old problems have become more acute and new problems have emerged due to 1) economic and population growth, 2) anthropogenic climate change, 3) an increasing recognition of the previously unaccounted-for water needs of both disadvantaged communities and ecosystems, but also 4) the growing complexity of inter-basin and cross-scale interactions, due to trade, large-scale infrastructure and land-use change patterns. We also need to manage the distribution of water availability and risk for users of different socio-economic characteristics, rather than merely focus on aggregate or average availability and risk (Brelsford et. al., 2017). There are many studies of inequality of water access and contaminant exposure in the environmental justice literature and development literature (Baisa et al., 2010; Tisdell, 2003). There are also studies about the conflict between urban and agricultural uses of water (Flörke et al. 2018), and the socio-ecological systems literature has focused on resource allocation in common-pool resource problems (Ostrom, 1993). However, analyzing the distribution of water quantity and quality across society is not currently a routine part of hydrological modeling (Zeitoun et al. 2016). These trends mean that social processes must now take center stage in the study and practice of water management for all fields. Given today's challenges, now is a critical time to extract general lessons from the historical record of institutional innovation.

QUESTIONS FOR FUTURE RESEARCH

In order to draw lessons from history and devise sensible approaches for the future, more consistent and commonly shared framing of characteristic challenges are needed. In the past, much socio-hydrology research has focused on modeling problems framed by different scientific domains and their modeling techniques, followed by attempts to couple the models using two-way feedbacks between the physical and social components (e.g. Di Baldassarre et al., 2013). Alternatively, we can view socio-hydrological systems as structurally co-constituted of natural, engineered, and social elements and think of characteristic problems as phenomena emerging from this structure. For example, the conjunction of allocated property rights, and landscape and hydroclimatic features, results in a given spatio-temporal distribution of water. This perspective goes beyond searching for evidence of feedbacks between the separately conceptualized natural and social domains, as has been the focus in the field of socio-hydrology (e.g. Di Baldassarre et al., 2015). Instead it encourages us to explore questions such as: What methods have failed or succeeded in addressing these challenges? What structural components of the system affect its resilience to hydrological events and through what mechanisms? Are there differences between successful and unsuccessful strategies to solve one of the characteristic management challenges? If so, how is success affected by institutional structures, socioeconomic context, and ecological conditions? How do people perceive hydrological risk and how do perceptions change with changing natural conditions? How do distributional heterogeneities in the consequences of an adverse event impede collective action to address it? Based on an understanding of their co-constituted elements, can general typologies of water systems and management strategies emerge?

We need more convergence in the ways different disciplines (in particular hydrology, economics, public policy and political science) formulate problems so that knowledge can accumulate across cases. Social scientists are encouraged to develop typologies of governance failures to generalize findings. They could also go beyond characterizing individual and collective decisions and cooperation dynamics and trace the effect of these social dynamics on natural systems. Finally, social scientists can address the paucity of comparative data on institutions. Natural scientists are encouraged to incorporate richer conceptions of social systems, in particular by considering the role that institutions play in water systems as distinct from the behavior of individuals such as in Anderies et al. (2006), Souza Filho et al. (2008), or Dell'Angelo et al. (2018). Process hydrologists might focus on developing modeling tools that are flexible, participatory, and open to extension to allow institutional scholars and stakeholders to use them in ways that are unanticipated. These tools should streamline the inclusion of both anthropogenic and natural processes - for example including the ability to model impervious surfaces of various roughness, urban contaminants and contagions, and hydraulic infrastructure. This leads to a focus on the adaptive capacity of a system emanating from its institutions and infrastructure, rather than predictive models of long-term coupled dynamics. Empirically, we must overcome the challenges of combining social with hydrological and ecological data, where the latter measure features of a continuous spatio-temporal field, while the former are discrete, often static, and may not coincide with the spatial scale at which hydrological outcomes emerge. Advances in computer science and hydrological modeling can help us combine these different types of data into more integrated and causal analyses (Ferraro et al., 2019; Müller & Levy, 2019). Advances in digitization of historical records, natural language processing, machine learning, and remotely sensed imagery can help us address the paucity of data on institutions and social structure e.g. (Lansing et al., 2017).

Finally, social and natural scientists are encouraged to observe and learn from the institutional responses to stress that are being tried by water managers around the world, and consider how these responses to local water challenges might be adapted across space, time, and scales. Collaborative decision-making strategies using techniques such as immersive computational tools and exploratory modeling can support interactions at the interface of science and policy, helping scientists communicate ranges of probable outcomes and helping policy-makers communicate to scientists ranges of plausible decisions. In turn, this scientific research should enhance decision-support systems, as well as inform sustainability science more broadly, especially since water management is a critical element of adapting to most environmental changes.

Data Availability Statement

N/A

LITERATURE CITED

Anderies, J. M. 2015. Understanding the Dynamics of Sustainable Social-Ecological Systems: Human Behavior, Institutions, and Regulatory Feedback Networks. *Bulletin of Mathematical Biology* 77(2): 259-80.

Anderies, J, M., M. Janssen, and E. Ostrom. 2004. A Framework to Analyze the Robustness of Social-Ecological Systems from an Institutional Perspective. *Ecology and Society* 9(1): 18.

Anderies, J. M., P. Ryan, and B. H. Walker. 2006. Loss of Resilience, Crisis, and Institutional Change: Lessons from an Intensive Agricultural System in Southeastern Australia. *Ecosystems* 9 (6): 865-78.

Baisa, B., L. W. Davis, S, W. Salant, and W. Wilcox. 2010. The Welfare Costs of Unreliable Water Service. *Journal of Development Economics* 92 (1): 1-12.

Beck, M. B. 1987. Water Quality Modeling: A Review of the Analysis of Uncertainty. *Water Resources* Research 23 (8): 1393-1442.

Boone, C. 2014. *Property and Political Order in Africa: Land Rights and the Structure of Politics*. Cambridge Studies in Comparative Politics. New York, NY: Cambridge University Press.

Brelsford, C., J. Lobo, J. Hand, and L. M. A. Bettencourt. 2017. Heterogeneity and Scale of Sustainable Development in Cities. *Proceedings of the National Academy of Sciences* 114(34): 8963-68.

Brewer, J., R. Glennon, A. Ker, and G. D. Libecap. 2007. Transferring Water in the American West: 1987-2005. *University of Michigan Journal of Law Reform. University of Michigan. Law School* 40(4): 1021-53.

Brown, C., and U. Lall. 2006. Water and Economic Development: The Role of Variability and a Framework for Resilience. *Natural Resources Forum* 30 (4): 306-17.

Coman, K. 2011. Some Unsettled Problems of Irrigation (1911). *The American Economic Review* 101(1): 36-48.

Davies, E. G. R., and S. P. Simonovic. 2011. Global Water Resources Modeling with an Integrated Model of the Social-economic-environmental System. *Advances in Water Resources* 34(6): 684-700.

Dell'Angelo, J., D'Odorico, P., and Rulli, M.C. 2018. The Global Water Grab Syndrome. *Ecological Economics* 143:276-285.

Di Baldassarre, G., H. Kreibich, S. Vorogushyn, J. Aerts, K. Arnbjerg-Nielsen, M. Barendrecht, P. Bates, et al. 2018. HESS Opinions: An Interdisciplinary Research Agenda to Explore the Unintended Consequences of Structural Flood Protection. *Hydrology and Earth System Sciences Discussions*, 1-11.

Di Baldassarre, G., M. Kooy, J. S. Kemerink, and L. Brandimarte. 2013. Towards understanding the dynamic behaviour of floodplains as human-water systems. *Hydrol. Earth Syst. Sci.*, 17(8):3235-3244.

Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, K. Yan, L. Brandimarte, and G. Blöschl. 2015. Debates-Perspectives on Socio-Hydrology: Capturing Feedbacks between Physical and Social Processes. *Water Resources Research* 51 (6): 4770-81.

Elshafei, Y., M. Sivapalan, M. Tonts, and M. R. Hipsey. 2014. A Prototype Framework for Models of Socio-Hydrology: Identification of Key Feedback Loops and Parameterisation Approach. *Hydrology and* Earth System Sciences 18 (6): 2141-66.

Ferraro, P. J., J. N. Sanchirico, and M. D. Smith. 2019. Causal Inference in Coupled Human and Natural Systems. *Proceedings of the National Academy of Sciences* 116 (12): 5311-18.

Fishman, R. M., T. Siegfried, P. Raj, V. Modi, and U. Lall. 2011. Over-Extraction from Shallow Bedrock versus Deep Alluvial Aquifers: Reliability versus Sustainability Considerations for India's Groundwater Irrigation. *Water Resources Research* 47, W00L05, doi:10.1029/2011WR010617

Flörke, M., C. Schneider, and R. I. McDonald. 2018. Water Competition between Cities and Agriculture Driven by Climate Change and Urban Growth. *Nature Sustainability* 1(1): 51-58.

Garrick, D., S. M. Whitten, and A. Coggan. 2013. Understanding the Evolution and Performance of Water Markets and Allocation Policy: A Transaction Costs Analysis Framework. *Ecological Economics* 88: 195-205.

Geels, F. W., and J. Schot. 2007. Typology of Sociotechnical Transition Pathways. *Research Policy*

36(3): 399-417.

Gohari, A., A. Mirchi, and K. Madani. 2017. System Dynamics Evaluation of Climate Change Adaptation Strategies for Water Resources Management in Central Iran. *Water Resources Management* 31(5): 1413-34.

Heikkila, T., E. Schlager, and M. W. Davis. 2011. The Role of Cross-Scale Institutional Linkages in Common Pool Resource Management: Assessing Interstate River Compacts. *Policy Studies Journal* 39(1): 121-45.

Hering, D., L. Carvalho, C. Argillier, M. Beklioglu, A. Borja, A. C. Cardoso, H. Duel, et al. 2015. Managing Aquatic Ecosystems and Water Resources under Multiple Stress--an Introduction to the MARS Project. *The Science of the Total Environment* 503-504: 10-21.

Holling, C. S. 1973. Resilience and Stability of Ecological Systems. *Annual Review of Ecology and* Systematics 4: 1-23.

Hornbeck, R., and P.Keskin. 2014. The Historically Evolving Impact of the Ogallala Aquifer: Agricultural Adaptation to Groundwater and Drought. *American Economic Journal. Applied Economics* 6(1): 190-219.

Lansing, J. S., S. Thurner, N. N. Chung, A. Coudurier-Curveur, Ç. Karakaş, K. A. Fesenmyer, and L. Y. Chew. 2017. Adaptive Self-Organization of Bali's Ancient Rice Terraces. *Proceedings of the National Academy of Sciences* 114(25): 6504-9.

Li, C., X. Cheng, N. Li, X. Du, Q. Yu, and G. Kan. 2016. A Framework for Flood Risk Analysis and Benefit Assessment of Flood Control Measures in Urban Areas. *International Journal of Environmental* Research and Public Health 13(8). https://doi.org/10.3390/ijerph13080787.

Libecap, G. D. 2011. Institutional Path Dependence in Climate Adaptation: Coman's 'Some Unsettled Problems of Irrigation. *The American Economic Review* 101(1): 64-80.

Liu, J., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, et al. 2007. Complexity of Coupled Human and Natural Systems. *Science* 317(5844): 1513-16.

Lubell, M., G. Robins, and P. Wang. 2014. Network Structure and Institutional Complexity in an Ecology of Water Management Games. *Ecology and Society* 19(4). http://www.jstor.org/stable/26269667.

Madani, K., O. M. Rouhani, and A. Mirchi. 2014. A Negotiation Support System for Resolving an International Trans-Boundary Natural Resource Conflict. *Environmental Modelling & Software* 51: 240-49.

Merz, B., S. Vorogushyn, U. Lall, A. Viglione, and G. Blöschl. 2015. Charting Unknown waters-On the Role of Surprise in Flood Risk Assessment and Management. *Water Resources Research* 51(8): 6399-6416.

Müller, M. F., and M. C. Levy. 2019. Complementary Vantage Points: Integrating Hydrology and Economics for Sociohydrologic Knowledge Generation. *Water Resources Research* 55(4): 2549-71.

Nelson, M. C., K. Kintigh, D. R. Abbott, and J. M. Anderies. 2010. The Cross-Scale Interplay between Social and Biophysical Context and the Vulnerability of Irrigation-Dependent Societies: Archaeology's Long-Term Perspective. *Ecology and Society* 15(3). https://doi.org/10.5751/ES-03389-150331.

Olsson, L., and A. Jerneck. 2018. Social Fields and Natural Systems: Integrating Knowledge about Society and Nature. *Ecology and Society* 23(3). https://doi.org/10.5751/ES-10333-230326.

Ostrom, Elinor. 1993. Design Principles in Long-Enduring Irrigation Institutions. *Water Resources* Research 29(7): 1907-1912.

Polasky, S., S. R. Carpenter, C. Folke, and B. Keeler. 2011. Decision-Making under Great Uncertainty: Environmental Management in an Era of Global Change. *Trends in Ecology & Evolution* 26(8): 398-404.

Preise, R., R. Biggs, A. De Vos, and C. Folke. 2018. Social-Ecological Systems as Complex Adaptive Systems: Organizing Principles for Advancing Research Methods and Approaches. *Ecology and Society* 23(4): 46, doi:10.5751/ES-10558-230446

Quinn, J. D., P. M. Reed, M. Giuliani, A. Castelletti, J. W. Oyler, and R. E. Nicholas. 2018. Exploring How Changing Monsoonal Dynamics and Human Pressures Challenge Multireservoir Management for Flood Protection, Hydropower Production, and Agricultural Water Supply. *Water Resources Research* 54(7): 4638-62.

Schlüter, M., K. Orach, E. Lindkvist, R. Martin, N. Wijermans, Ö. Bodin, and W. J. Boonstra. 2019. Toward a Methodology for Explaining and Theorizing about Social-Ecological Phenomena. *Current Opinion in Environmental Sustainability*, Open Issue 2019, 39: 44-53.

Scholz, J. T., and C-L. Wang. 2006. Cooptation or Transformation? Local Policy Networks and Federal Regulatory Enforcement. *American Journal of Political Science* 50(1): 81-97.

Sivapalan, M., and G. Blöschl. 2015. Time Scale Interactions and the Coevolution of Humans and Water. *Water Resources Research* 51(9): 6988-7022.

Souza Filho, F. Assis, U. Lall, and R. La Laina Porto. 2008. Role of Price and Enforcement in Water Allocation: Insights from Game Theory. *Water Resources Research* 44, W12420, doi:10.1029/2007WR006163

Srinivasan, V., E. F. Lambin, S. M. Gorelick, B. H. Thompson, and S. Rozelle. 2012. The Nature and Causes of the Global Water Crisis: Syndromes from a Meta-Analysis of Coupled Human-Water Studies. *Water Resources Research* 48(10). https://doi.org/10.1029/2011WR011087.

Thompson, S. E., M. Sivapalan, C. J. Harman, V. Srinivasan, M. R. Hipsey, P. Reed, A. Montanari, and G. Blöschl. 2013. Developing Predictive Insight into Changing Water Systems: Use-Inspired Hydrologic Science for the Anthropocene. *Hydrology and Earth System Sciences* 17(12): 5013-39.

Tisdell, J. G. 2003. Equity and Social Justice in Water Doctrines. *Social Justice Research* 16(4): 401-16.

Xepapadeas, A. 2011. The Economics of Non-Point-Source Pollution. *Annual Review of Resource* Economics 3(1): 355-73.

Zeitoun, M., B. Lankford, T. Krueger, T. Forsyth, R. Carter, A. Y. Hoekstra, R. Taylor, et al. 2016. Reductionist and Integrative Research Approaches to Complex Water Security Policy Challenges. *Global* Environmental Change 39: 143-54.

Fig. 1. Water systems are a distinct class of coupled systems because they present a finite set of recurrent management challenges: disturbances of too much, too little, or wrong-quality water. These challenges can manifest alone or in combination at different temporal and spatial scales and have differential impacts within and across social groups. Thus, water systems provide us with a long historical record of institutional innovation in response to the management challenges as they appeared at increasingly large scales of social organization, from small farming settlements to nation states.