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COMMENTARY

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Key Points:
- Socio-hydrologic models can be seen as hypotheses of coupled system dynamics
- Robust validation is required across multiple basins
- Trade-offs between generality, precision, and realism are required

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Debates—Perspectives on socio-hydrology: Socio-hydrologic modeling: Tradeoffs, hypothesis testing, and validation

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Abstract Socio-hydrology focuses on studying the dynamics and co-evolution of coupled human and water systems. Recently, several new socio-hydrologic models have been published that explore these dynamics, and these models offer unique opportunities to better understand these coupled systems and to understand how water problems evolve similarly in different regions. These models also offer challenges, as decisions need to be made by the modeler on trade-offs between generality, precision, and realism. In addition, traditional hydrologic model validation techniques, such as evaluating simulated streamflow, are insufficient, and new techniques must be developed. As socio-hydrology progresses, these models offer a robust, invaluable tool to test hypotheses about the relationships between aspects of coupled human-water systems. They will allow us to explore multiple working hypotheses to greatly expand insights and understanding of coupled socio-hydrologic systems.

1. Introduction

As a science, hydrology has typically been focused on natural, pristine conditions to better understand hydrologic processes. However, pristine catchments are the exception rather than the norm. Humans modify the hydrologic cycle in myriad different ways, and in turn, the hydrologic cycle influences human behavior and decision-making. Socio-hydrology is based on the premise that human systems (e.g., society) and water systems are coupled in some regions such that the human and water systems coevolve, with potentially similar dynamics emerging in different regions. This foundation is connected to the communities of scholars who define their work as focused on coupled natural-human systems or social-ecological systems. But the unique characteristics of hydrological systems present an opportunity to define the nature of socio-hydrological interactions with particular implications for how those interactions can be modeled.

In the Anthropocene, humans significantly affect the water cycle. Agriculture is the largest consumptive user of freshwater, both globally and in the United States. In addition to agriculture, water is needed for domestic and industrial use. Both of these are not significant consumptive uses, but having water available when needed is critical. To meet water demands, there have been large-scale transfers of water via canals from water-rich regions to water-poor regions. The quintessential example is California's federal and state water infrastructure, but this is not the only region: this has also occurred in India and is currently being developed in China. Dams have been built for water supply storage, flood control, hydropower generation, and navigation. In the process, they have led to fragmented river systems with impacts on the hydrologic cycle [*Graf*, 1999]. Globally, water withdrawals and reservoirs have decreased annual discharge to the oceans by 2.7% with significant changes to the seasonal cycle of streamflow [*Doll et al.*, 2009].

Surface water quantity is not the only component of the water system significantly affected by human activities. Groundwater withdrawals have been leading to groundwater depletion in India [*Rodell et al.*, 2009], the Middle East [*Voss et al.*, 2013], China [*Wada et al.*, 2010], and the United States [*Konikow and Kendy*, 2005; *Famiglietti et al.*, 2011]. Pollution from human activities contaminates both streamflow and groundwater, which can then affect the riverine ecosystem, downstream users, and lead to anoxia and hypoxia as seen in the Gulf of Mexico due to agriculture in the Mississippi River Basin [*Rabalais et al.*, 2002]. Crop-water dynamics have critical implications for food production, particularly in dryland ecosystems where drought-induced crop failure is becoming increasingly common.

In turn, many elements of water availability have critical impacts on human development, and modeling presents one mechanism to understand how to mitigate the negative consequences from poor water management. Acknowledging that arid lands in the western U.S. were less productive than in the East, the allotment of land from the Homestead Act was increased from 160 acres to up to 640 acres for western Nebraska. In the Tarim River Basin in China, the extremely arid climate limited human populations until water infrastructure was built [*Liu et al*., 2014]. On a broader scale, *Brown and Lall* [2006] showed that national GDP is related to the interannual and intraannual variability of precipitation for nonoil-rich nations. Drought and floods negative affect GDP growth [*Brown et al*., 2013], such that a region's hydroclimatological extremes may have affected some regions' historical growth.

There is a substantial amount of human-water work that does not explicitly model feedbacks between human and water components in a system. Indeed, in an effort to produce the least complex model possible while still adequately representing system dynamics, some models need not necessarily include coevolution of social and hydrological dynamics. For example, some models may take population growth as exogenous in order to develop a scenario-based model of water demand. Beyond these scenario-based modeling approaches, there is a vast realm where coevolution between social and hydrological dynamics can be modeled. For example, in the same population growth/water demand application, it may be necessary to incorporate how water conservation measures may evolve (e.g., xeriscaping as a land use policy in rapidly growing urban areas) in order to evaluate what population size can be adequately served by how much water. Hydrological modeling is still developing the methodological approaches necessary to advance our understanding of how these social and hydrological systems are intertwined. In particular, incorporating behavioral responses to water scarcity and hydrologic extremes in hydrological models constitutes a rich arena for future innovations. These innovations may lead to better policy-relevant science as well as an increased understanding to make improved predictions, which can be important in water resource planning, particularly under climate uncertainty.

The premise behind socio-hydrology, that there are two-way feedbacks that lead to coevolution of the human and water systems, may be considered a hypothesis. Recent literature has begun to validate the core hypothesis through case studies of individual regions [e.g., *Kandasamy et al*., 2014; *Liu et al*., 2014]. A synthesis of many case studies showed that four dominant water patterns existed in regions of water crisis [*Srinivasan et al*., 2012], which leads credence to the premise that common dynamics may emerge across different regions. This then leads to the possibility of modeling the coupled human-water systems, and several recent studies have begun to do this [*Di Baldassarre et al*., 2013; *Srinivasan*, 2015; *Elshafei et al*., 2014; *van Emmerik et al*., 2014]. This paper discusses how models can be used to advance our understanding of the dynamics between human and water systems, some of the trade-offs modelers will have to make to describe complex systems, and how comprehensive model validation is needed.

2. Understanding and Modeling the Coupled System

Socio-hydrology is still in its infancy, and we are still learning what the right questions to ask are. The term "socio-hydrology" has been introduced relatively recently [*Sivapalan et al*., 2012], but long ago the term "hydro-social" was used to acknowledge the need to understand the connection between people and water. This previous use of the term "hydro-social" did not explicitly acknowledge the coevolution of social systems and hydrological systems nor promote an investigation of methods to understand the nature of the complex feedbacks between these systems. Indeed, the term "socio-hydrology" both promotes the concept that social systems and hydrological systems are inherently coupled and cannot be adequately represented independently. Fundamentally, we need to develop an understanding of how human-water systems are coupled and how they develop and evolve. For example, how do the four dominant patterns of water crises [*Srinivasan et al*., 2012] emerge in multiple regions? What is the relative role of climate versus the nature of water demands versus governance structures? No single disciplinary field can answer these questions, but studying them in the context of complex, coupled systems may allow us to begin to answer them. This is much the same vision that has driven the study of socioecological systems (also referred to as coupled natural-human systems in the literature), a subset of which is constituted by socio-hydrological dynamics. For now, we do not suggest that socio-hydrology is a separate, new scientific discipline. Rather, we are more concerned with how an acknowledgement of the principles behind socio-hydrology can

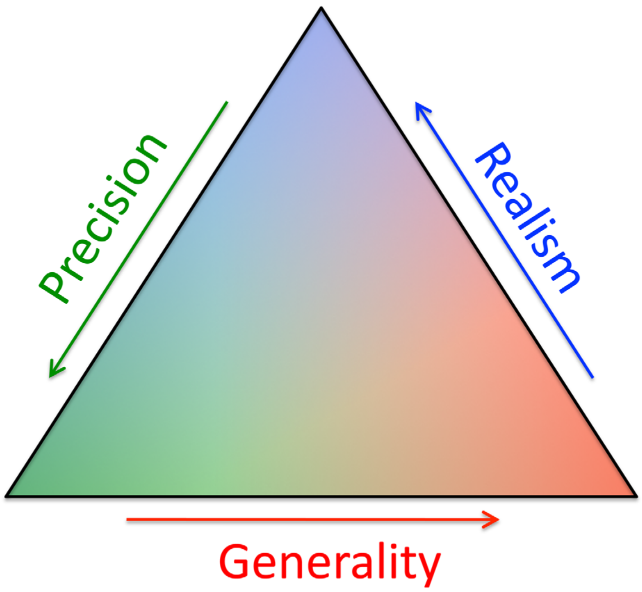

Figure 1. Tradeoffs in model building between generality, precision, and realism.

enable modelers to produce better representations of systems with tight couplings and rich feedbacks between social and hydrological domains.

There is a range of modeling approaches that can help move in this direction including agent-based models, hydroeconomic models, and conceptual models (defined here as consisting of coupled, nonlinear different equations). For illustrative purposes in this paper, we will primarily focus on these conceptual models due to their relative simplicity. These models can be employed for a variety of applications. As *Di Baldassarre et al*. [2015] used theirs, a model can highlight the tradeoffs and effects of different approaches to flooding. By adjusting the parameters, the sensitivity of a system can be evaluated, and the effects of different policy choices, in this case infrastructure versus a green, "living with floods" approach, can be explored in terms of damages and economic growth. This is similar to models developed for policy and decision-making, where the effects of different strategies for water resources are explored [e.g., *Gober et al*., 2011]. These scenario analyses answer the "what if" question of how a system may behave under certain conditions, such as climate, changing human activities through water usage or policy, or the sensitivity to model parameters. The conceptual models have feedbacks built into the model structure; this may or may not be the case for policy and decision-making models. The study of social-ecological systems has highlighted the utility of scenario-based approaches to understanding the coupled dynamics of human and natural systems, particularly in the face of uncertainty [*Peterson et al*., 2003]. These scenario-based approaches often make use of participatory methods to explicitly integrate stakeholder decision-making into models of social-ecological system dynamics [*Walker et al*., 2002; *Kok*, 2009].

Agent-based models (ABMs) present a valuable avenue to investigate coupled feedbacks in social-ecological systems. ABMs are particularly useful because they enable diverse agents (or actors) to be represented as heterogeneous decision-makers are that interacting to produce emergent system outcomes. For example, the diffusion of technology (e.g., adoption of drip irrigation) may occur through experimentation and communication where early adopters first assess whether a new strategy is advantageous. The nature of this social-technical diffusion may be affected by the characteristics of actors where some are more receptive to new technologies while others may be resistant to changing their ways. The result is that technologies may diffuse differently in separate areas as a function of cultural dynamics, demographic characteristics, and governance arrangements. ABMs can be populated with agents with different characteristics and have been widely used to investigate such diffusion dynamics in agricultural systems.

3. Tradeoffs Made in Modeling Structure

Bringing together approaches to understand the coevolution of socio-hydrologic systems results in potentially complex (and complicated) systems [*Manson*, 2001; *Manson and O'Sullivan*, 2006]. Tools are needed to manage this complexity to create simple models that are useful and easy to communicate while at the same time acknowledging that some modeling applications require a level of complexity that results in models that are difficult to make transparent to stakeholders. In his classic 1966 paper, Richard Levins describes an approach to managing the complexity of systems that emerged from the development of a "modern" understanding of population biology (resulting from the unification of population ecology and population genetics) [*Levins*, 1966]. Levins illustrates that when crafting models of complex systems, we are faced with several tradeoffs between generality, realism, and precision (Figure 1) as we build models with "the overlapping but not identical goals of understanding, predicting, and modifying nature" [*Levins*, 1966, p. 422]. Models may sacrifice generality for realism and precision, focusing on accurate predicative ability for specific cases, such as resource quantity. Models may sacrifice realism for precision and generality, and start with a goal of precision and progressively increase realism by altering the assumptions of the model. Finally, models may sacrifice precision for generality and realism, choosing to explore quantitative relationships without a strong focus on mathematical precision and form.

Levins presents these tradeoffs as a set of strategies for modeling complex systems, suggesting that in the end, a suite or cluster of robust models may be needed to fully develop a theory or hypothesis. Initially as socio-hydrology explores its core hypothesis, it may be looking for models that are capable of exploring the robustness of coevolutionary patterns and may seek to focus on the latter two forms of tradeoffs, seeking generalizability and precision of models, and working in more complex relationships that describe the reality of decision making later. Socio-hydrology may also look to the development of social-ecological systems modeling for cues on how to apply this modeling strategy. For example, *Schlüter et al*. [2012] describe how social-ecological systems modeling seeks to represent the complexity of decision-making behaviors, a departure from some economic models that do not include heterogeneous agent decision-making. Instead, the social-ecological approach describes behavior as a function of both the agent and the structures that agent operates and perceives within. The incorporation of more "social realism" in modeling (in particular agent-based modeling) may make models difficult to use and complex to communicate [*Schlüter et al*., 2012]. Because socio-hydrology can be viewed as embedded in a larger social-ecological system, it behooves us to learn from modeling approaches and trade-offs taken in the social-ecological systems literature.

4. Testing the Hypotheses of Coevolution in Socio-hydrological Models

Several conceptual socio-hydrology models, consisting of coupled, nonlinear differential equations, have been published in the past 2 years. Specifically, that of *Di Baldassarre et al*. [2013] explored the interactions between human settlements and flooding, and *Srinivasan* [2015] developed a model of human-water dynamics in Chennai, India. *van Emmerik et al*. [2014] and *Elshafei et al*. [2014] developed generalized conceptual models of the dynamics between society and hydrology in river basins with significant irrigation. Both of these latter models consist of equations for the hydrologic water balance, ecosystems, population, and some sort of environmental awareness/sensitivity. Other aspects, such as irrigation, are included in both models but in different forms.

If we take any of these models as an example, we will find a series of equations that link hydrology and social dynamics into a conceptual model. The overall conceptual model is a hypothesis about how different systems interact with each other. Each individual equation may also be considered a hypothesis about how the variable of interest is related to others. To choose an equation solely for its simplicity, equation (1) of *van Emmerik et al*. [2014] lays out the governing equation for irrigation as follows:

$$\frac{d\alpha_i}{dt} = \alpha_\tau(T) + \alpha_S(S_i) + \alpha_E(E)$$

where α_i is the irrigated area per capita, $\alpha_\tau(T)$ is a function of technology, $\alpha_S(S)$ is a function of water storage, and $\alpha_E(E)$ is a function of community environmental awareness. This equation is a hypothesis of how irrigated area changes as a result of water availability, which is affected by both exogenous and endogenous components to the model. For example, is irrigated area per capita the relationship driving changes in irrigated area or is it driven by the cost-benefit analysis as in *Elshafei et al*. [2014]? Are technology, water storage, and community environmental awareness the three determinants of irrigated area growth or is this a region-specific equation? If the correct drivers are included, is the functional form of the equation correct?

Many of the equations in these conceptual models (or any type of model) can be considered as hypotheses of the relationship that exists between different variables [*Di Baldassarre et al*., 2013]. The equation as hypothesis consists of two parts: which variables are important to predicting the variable of interest and the functional form of the equation. In socio-hydrology, we are still currently learning about how to conceptualize and model the coupled human-water system. As such, when we develop the model equations, we are creating hypotheses about the relationships between different aspects of the system. Not all equations will be a hypothesis: mass conservation is an example of an equation that would not require validation.

Just as many of the individual equations can be considered as a hypothesis to be tested, the overall model can be viewed the same way, allowing the hypothesis of coevolution in socio-hydrological systems to be tested. Are all the exogenous drivers included? Are all the necessary dynamics between different components of the socio-hydrologic system? Are emergent dynamics, such as a shift in prioritizing the environment, captured by the model? The overall model performance is typically the level at which traditional hydrologic models are tested and validated. For example, the simulated streamflow is compared against the observed streamflow to determine if the model can reasonably replicate the real hydrologic system. This would be analogous to validating emergent dynamics in socio-hydrologic models. The traditional hydrologic model consists of many equations for many processes, including evapotranspiration, infiltration, soil moisture, and runoff generation, all of which are interlinked. If the model does a poor job at simulating runoff, it could be due to problems in the soil moisture dynamics. In socio-hydrologic models, the same phenomena can be true, in which the overall model performance of one variable may replicate the historical trajectory of the system, but this does not mean that the right answer is obtained for the right reasons.

5. Multiple Working Hypotheses

The method of multiple working hypotheses was proposed by *Chamberlin* [1890], who warned that as scientists who are human, we will naturally be partial to our hypothesis or model as it is our "intellectual child." By creating multiple working hypotheses, we avoid falling into the pitfall of accepting our first theory/model/hypothesis as true [*Chamberlin*, 1890]. *Clark et al*. [2011] laid out this approach for catchment hydrology models, arguing that as a community, hydrology has failed to use models as hypotheses to increase the understanding of hydrologic processes and the overall hydrologic system. This holds true for socio-hydrology models as well.

The current state of understanding of socio-hydrology is still evolving: we know from a handful of case studies that human and water systems can coevolve, affecting one another across a range of time scales, but we do not yet know the nature of the dynamics of many of these interactions. Do humans continuously affect the hydrologic cycle in time while the hydrologic cycle only affects water management practices in times of water scarcity? Are there common thresholds where the hydrology affects humans across different regions, and if so, what is the nature of these thresholds (e.g., is it a balance between naturally available water and human demands)? How can researchers and practitioners determine at what spatial and temporal extents to model human-water dynamics? Some applications may not require a coevolutionary approach while others do. Defining the conditions under which a socio-hydrological model needs to incorporate coevolution could help practitioners and decision-makers determine under what conditions this coupled approach is necessary. In catchment hydrology, we have established theories of hydrologic processes, such as infiltration-excess and saturation-excess runoff generation, that inform pure hydrologic model building. In socio-hydrology, we are in the process of generating initial hypotheses rather than implementing existing theory, and we can think of socio-hydrologic models as just that, hypotheses of the system's coupling and feedbacks.

The future of socio-hydrologic conceptual modeling could easily become a plethora of models, each with their own coupled differential equations. Rather than providing insight into the system, these could easily obfuscate our understanding, devolving into model intercomparisons. If model development begins with the premise of multiple working hypotheses, then this can further the field of socio-hydrology significantly. An example of this would be how to model a society's response to water scarcity. There is a range of possible responses, such as living with scarcity, building infrastructure, implementing water savings measures, or reallocating water for ecosystem services. The response may depend on how a society values the environment: in some places a river drying up may be acceptable while in others this could be completely unacceptable. The response may also depend on the condition of the environment, in that sometimes conditions seem to need deteriorate before action is taken. The form of the equation would look different, depending on how, why, and when a society responds or values the environment.

It is important to acknowledge that models are imperfect representations of an actual system as are the individual equations comprising the model. As such, a given equation or model will have an imperfect fit. However, by using different representations of an equation (or model), the goodness-of-fit can be evaluated, such that the equation form with the best fit would be chosen as the best hypothesis of the relationship between variables. In practice, this could be done in several ways. The first would be to hypothesize a priori multiple equations for the variable of interest. The second would be to determine the functional form during model calibration using automated methods to determine the best fit and parameters of interest. Regardless of the approach taken, this would allow for multiple hypotheses, or equations, to be explored to allow for the most representative model of the system, even if the resulting model is by definition imperfect.

6. How to Validate and Hypothesis Test With These Models

For the central idea behind socio-hydrology—that there are dynamics and feedbacks between human and water systems resulting in two-way coupling—to be true, then patterns may emerge across a range of case studies. For example, the model of *Di Baldassarre et al.* [2013] should be able to generally produce results seen in a range of socio-hydrologic systems—with some locations choosing a more engineered approach with flood defenses and others choosing to live with floods and move back from the river. The models of *van Emmerik et al.* [2014] and *Elshafei et al.* [2014] should be able to replicate the dynamics in other heavily irrigated basins outside of the basin for which it was developed. Exploring the nonlinear, potentially surprising and interesting, dynamics of the socio-hydrologic system through modeling can provide insight into the system's coupling, but it is an exercise in the conceptual world [e.g., *Di Baldassarre et al.*, 2015], without knowing if it represents the true system, its feedbacks and linkages, and its response to external drivers. In socio-hydrology, we need to develop validation methodologies, or hypothesis tests, of the models.

In traditional hydrologic modeling, parameter calibration is performed for a subset of the available observed time series, with validation of the parameters for the remaining portion of the time series. For socio-hydrologic models, using the traditional mode of calibration may not be feasible. For example, the hypothesized trajectory of environmental awareness in the Australian basins requires focus on the entire 20th century to capture the dynamics, as there was only one shift in environmental awareness throughout the century [*Kandasamy et al.*, 2014]. This therefore does not allow for separating the time series into model calibration and validation periods. Consequently, different approaches may be appropriate and require development. For example, identifying basins with similar water usage in a region with similar water laws could allow for calibration of parameters in one basin and validation on several other basins. However, this may also pose problems, as the social system and its coupling to the physical system may preclude universal dynamics. In addition, it is possible that how the two systems coevolved is one plausible path among many, or it is also possible that the nature of the social dynamics (i.e., economic, demographic, cultural) that are represented in the model may result in different trajectories and model behaviors. The model could produce a range of plausible trajectories, and validation would involve verifying that the observed historical trajectory is one of the modeled scenarios. This is analogous to how global circulation models are validated for 20th century temperature trends.

Given the premise that many of the individual equations are hypotheses as is the system of equations, each portion of the model should be validated. Do the individual equations represent the system according to the data? Are the equations overly parameterized? Does the relationship described in the equation exist over more than one region or is this an isolated case? Does data even exist to validate some of these equations? Are the relationships between different system components constant in time? In the hydrologic literature, *Kumar* [2011] discussed this as dynamic connectivity, such that relationships may be ephemeral and arise with thresholds. Social-ecological systems theory suggests that threshold dynamics related to actions that emerge to solve environmental problems are driven by perception of the magnitude of problems and the potential pay-off [*Scheffer and Westley*, 2007]. This could be the case for environmental awareness and hydrologic systems. A number of papers in a recent special issue in *Hydrologic and Earth System Sciences* showed that environmental awareness arose after environmental conditions became degraded; in general, environmental awareness did not spring up under unpolluted, unaffected hydrologic systems [*Troy et al*., 2015]. This implies that threshold dynamics exist in coupled human-water systems.

The difficulty lies in identifying and pulling together the data required for many case studies with comparable data to enable different models to be tested across time and space [*Braden et al*., 2014; *Magliocca et al*., 2014]. A multitude of case studies will allow for both statistical analysis and modeling to test specific hypotheses regarding the dynamics in socio-hydrological systems. A library of case studies will also allow for robust development of equations to describe the system dynamics rather than equations that fit the system of interest because the outcome is known and prescribed. It will also allow for exploring the relative importance of different drivers in different systems. For example, if we know a model is robust and not overparameterized to fit a given basin [*Levins*, 1966], then we can begin to use the model to explore interesting, essential questions to our understanding of socio-hydrology. But it should be acknowledged that some system components will be critical to one system while irrelevant in another. For example, the salient dynamic in one system may be population growth whereas in another it may be increasing climate variability. Testing the performance of models will require a sufficient number of cases with sufficiently complete data that models can be tested for many instances of particular socio-hydrological contexts. For the moment, it is an unanswered question how many cases would prove sufficient for this kind of assessment.

7. Conclusions

Although hydrology commonly focuses on pristine basins to understand hydrologic processes, the world is increasingly dominated by human activities that disrupt the natural hydrologic cycle. Thus advances are needed in order to understand how to incorporate these social-dynamics and social-hydrological interactions in models. The socio-hydrology concept has the potential to increase our understanding of coupled human and water systems through the overt recognition of coevolution in socio-hydrological systems and catalyzing the development of hydrological models that incorporate these dynamics. Many regions are facing water stress, often due to human water requirements, and it is possible there are commonalities to these water problems. Identifying the dynamics between human society and the water system can potentially lead to understanding how these water problems evolve and if there are common elements that dictate how a society will respond, which can in turn lead to better prediction, planning, and decision-making.

Many of the current socio-hydrologic models consist of a series of coupled differential equations that have been able to capture the dynamics of the watershed of interest. At this point, it is unclear if the models' ability to replicate the historical trajectories of coupled human-water dynamics is because the models have so many calibrated parameters that they can capture any dynamics or if it is because the mathematical model accurately captures the relationships that exist. By treating models as hypothesis tests, this uncertainty in overparameterization can be overcome. Using multiple hypotheses (or multiple model forms), we can begin to robustly test and accept the dynamics, relationships, and perhaps threshold behaviors of the coupled socio-hydrologic system.

To do this, the models will need to be applied over a variety of case studies, rather than one single region. This presents challenges with data availability. In general, precipitation and streamflow data will be available, but water usage data are often difficult to find. Even more difficult is the social data beyond population that might be needed to validate a model. For intangibles like environmental awareness, creative proxies can be used. *Elshafei et al*. [2014] used membership in the environmental organizations as a proxy for caring for the environment. Coming up with other creative proxies for which data might exist would lead to robust ways of either parameterizing or validating models.

This paper focused on conceptual, or analytical, models as several have been published in the past year, and their simplicity of form provides good examples of the points made above. However, many of the arguments about trade-offs and models as hypotheses apply to the broad class of socio-hydrologic models that incorporate human and water systems. Models can be used a tool to develop and advance socio-hydrologic theory about the dynamics and feedbacks about coupled water-human systems. Socio-hydrology has the potential to greatly increase our understanding about how water and human systems coevolve. It remains an open question whether the coevolution is unique to place or if common trajectories exist, and utilizing socio-hydrologic models across a range of case studies has the potential to answer this fundamental question. However, to do this, these models require robust validation and the right balance between generality, precision, and realism.

8. Post Script

The other commentaries and the paper by *Di Baldassarre et al.* [2015] that sparked this debate make different points about socio-hydrology and socio-hydrologic models, contributing to the ongoing dialog of what socio-hydrology as an interdisciplinary field will look like in the future. As the commentaries noted, incorporating human behavior in models is difficult. *Loucks* [2015] points out that human behavior is often unpredictable, providing several examples of human behavior that exacerbated rather than reduced flood risk. This poses a challenge for socio-hydrologic modeling: models can be biased based on the modeler's perception of what the human behavior should be [*Loucks*, 2015]. In addition, societal values and experiences with flooding can lead to diverging policy responses, such as the differences seen in U.S., UK, and Canadian flood policy [*Gober and Wheater*, 2015]. These different policies raise interesting questions. Are the differences between the three countries so large that the response to policy would vary greatly? Or is what happened in the past one possible trajectory of many that a society could have taken, such that the US could have ended up with Canada's flood policy with only slight changes in the events leading to the policies? *Gober and Wheater* [2015] also raise the interesting point that the media shapes much of society's flood risk perception, such that floods taking place in one place may affect flood risk perceptions in another. Moreover, media discourse encapsulates the histories and cultures of specific places that can translate into behavior and responses to water-related crises [*Sonnett et al.*, 2006]. The historical and cultural drivers and processes of social systems may pose further challenges for socio-hydrologic modeling [*Stepp et al.*, 2003].

Di Baldassarre et al. [2015] represent a significant first step toward socio-hydrologic flood risk modeling. Their model represents social dynamics in a simplified manner, critically acknowledging the adaptive behaviors of actors rather than what can be overly simplistic scenario-based approaches. Nevertheless, incorporating the complexity of human behavior into mathematical models poses a significant challenge. Simply developing robust methods of calibrating and validating complex socio-hydrological models, and the empirical data to do so, is a daunting prospect. However, just because it is difficult, does not mean it should not be done. As both *Sivapalan* [2015] and *Loucks* [2015] point out: if the hydrologic community does not engage in incorporating human behavior into models, someone else will, possibly poorly. There are new opportunities for hydrological modelers and social science modelers to work together to improve our understanding of how future water problems may affect social and environmental systems. Perhaps at no other time have policy makers been so attuned to water issues [e.g., *Bakker*, 2012]. For example, the two-pronged challenge of potentially increasing water scarcity combined with increasing demand for water resources requires a change in how water users perceive future water availability and how policy makers develop strategies for equitable water distribution. A socio-hydrological approach to modeling, that acknowledges the coevolution of social and hydrological systems, is one mechanism that can accelerate this understanding.

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References

Bakker, K. (2012), Water security: Research challenges and opportunities, *Science*, *337*(6097), 914–915.
Braden, J., M. Jolejole-Foreman, and D. Schneider (2014), Humans and the water environment: The need for coordinated data collection, *Water*, *6*(1), 1–16, doi:10.3390/w6010001.
Brown, C., and U. Lall (2006), Water and economic development: The role of variability and a framework for resilience, *Nat. Resour. Forum*, *30*(4), 306–317.
Brown, C., R. Meeks, Y. Ghile, and K. Hunu (2013), Is water security necessary? An empirical analysis of the effects of climate hazards on national-level economic growth, *Philos. Trans. R. Soc. A*, *371*(2002), 20,120,416–20,120,416, doi:10.1038/415680a.
Chamberlin, T. C. (1890), The method of multiple working hypotheses, *Science*, *15*, 92–96.
Clark, M. P., D. Kavetski, and F. Fenicia (2011), Pursuing the method of multiple working hypotheses for hydrological modeling, *Water Resour. Res.*, *47*, W09301, doi:10.1029/2010WR009827.
Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, J. L. Salinas, and G. Bloschl (2013), Socio-hydrology: Conceptualising human-flood interactions, *Hydrol. Earth Syst. Sci.*, *17*(8), 3295–3303, doi:10.5194/hess-17-3295-2013.
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 Resour. Res.*, *51*, doi:10.1002/2014WR016416, in press.
Doll, P., K. Fiedler, and J. Zhang (2009), Global-scale analysis of river flow alterations due to water withdrawals and reservoirs, *Hydrol. Earth Syst. Sci.*, *13*(12), 2413–2432.

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, *Hydrol. Earth Syst. Sci.*, *18*(6), 2141–2166, doi:10.5194/hess-18-2141-2014.

Famiglietti, J. S., M. Lo, S. L. Ho, J. Bethune, K. J. Anderson, T. H. Syed, S. C. Swenson, C. R. de Linage, and M. Rodell (2011), Satellites measure recent rates of groundwater depletion in California's Central Valley, *Geophys. Res. Letters*, *38*, L03403, doi:10.1029/2010GL046442.

Gober, P., and H. S. Wheater (2015), Debates—Perspectives on socio-hydrology: Modeling flood risk as a public policy problem, *Water Resour. Res.*, *51*, doi:10.1002/2015WR016945, in press.

Gober, P., E. A. Wentz, T. Lant, M. K. Tschudi, and C. W. Kirkwood (2011), WaterSim: A simulation model for urban water planning in Phoenix, Arizona, USA, *Environ. Plann. B*, *38*(2), 197–215, doi:10.1068/b36075.

Graf, W. L. (1999), Dam nation: A geographic census of American dams and their large-scale hydrologic impacts, *Water Resour. Res.*, *35*(4), 1305–1311.

Kandasamy, J., D. Sounthararajah, P. Sivabalan, A. Chanan, S. Vigneswaran, and M. Sivapalan (2014), Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: A case study from Murrumbidgee River basin, Australia, *Hydrol. Earth Syst. Sci.*, *18*(3), 1027–1041, doi:10.5194/hess-18-1027-2014.

Kok, K. (2009), The potential of Fuzzy Cognitive Maps for semi-quantitative scenario development, with an example from Brazil, *Global Environ. Change*, *19*(1), 122–133, doi:10.1016/j.gloenvcha.2008.08.003.

Konikow, L. F., and E. Kendy (2005), Groundwater depletion: A global problem, *Hydrogeol. J.*, *13*(1), 317–320, doi:10.1007/s10040-004-0411-8.

Kumar, P. (2011), Typology of hydrologic predictability, *Water Resour. Res.*, *47*, W00H05, doi:10.1029/2010WR009769.

Levins, R. (1966), The strategy of model building in population biology, *Am. Sci.*, *54*(4), 421–431.

Liu, Y., F. Tian, H. Hu, and M. Sivapalan (2014), Socio-hydrologic perspectives of the co-evolution of humans and water in the Tarim River basin, Western China: The Taiji–Tire model, *Hydrol. Earth Syst. Sci.*, *18*, 1289–1303, doi:10.5194/hess-18-1289-2014.

Loucks, D. P. (2015), Debates—Perspectives on socio-hydrology: Simulating hydrologic-human interactions, *Water Resour. Res.*, *51*, doi: 10.1002/2015WR017002, in press.

Magliocca, N. R., D. G. Brown, and E. C. Ellis (2014), Cross-site comparison of land-use decision-making and its consequences across land systems with a generalized agent-based model, edited by R. Huerta-Quintanilla, *PLoS One*, *9*(1), e86179, doi:10.1371/journal.pone.0086179.

Manson, S., and D. O'Sullivan (2006), Complexity theory in the study of space and place, *Environ. Plann. A*, *38*(4), 677–692, doi:10.1068/a37100.

Manson, S. M. (2001), Simplifying complexity: A review of complexity theory, *Geoforum*, *32*(3), 405–414.

Peterson, G. D., G. S. Cumming, and S. R. Carpenter (2003), Scenario planning: A tool for conservation in an uncertain world, *Conserv. Biol.*, *17*(2), 358–366.

Rabalais, N. N., R. E. Turner, and W. J. Wiseman (2002), Gulf of Mexico Hypoxia, a.k.a. "The Dead Zone," *Annu. Rev. Ecol. Syst.*, *33*(1), 235–263, doi:10.1146/annurev.ecolsys.33.010802.150513.

Rodell, M., I. Velicogna, and J. S. Famiglietti (2009), Satellite-based estimates of groundwater depletion in India, *Nature*, *460*(7258), 999–1002.

Scheffer, M., and F. R. Westley (2007), The evolutionary basis of rigidity: Locks in cells, minds, and society, *Ecol. Soc.*, *12*(2), 36.

Schlüter, M., et al. (2012), New horizons for managing the environment: A review of coupled social-ecological systems modeling, *Nat. Resour. Model.*, *25*(1), 219–272.

Sonnett, J., B. J. Morehouse, T. D. Finger, G. Garfin, and N. Rattray (2006), Drought and declining reservoirs: Comparing media discourse in Arizona and New Mexico, 2002–2004, *Global Environ. Change*, *16*(1), 95–113.

Sivapalan, M. (2015), Debates—Perspectives on socio-hydrology: Changing water systems and the "tyranny of small problems"—Socio-hydrology, *Water Resour. Res.*, *51*, doi:10.1002/2015WR017080, in press.

Sivapalan, M., H. H. G. Savenije, and G. Blöschl (2012), Socio-hydrology: A new science of people and water, *Hydrol. Processes*, *26*(8), 1270–1276, doi:10.1002/hyp.8426.

Srinivasan, V. (2015), Re-imagining the past-Use of counterfactual trajectories in socio-hydrological modelling: The case of Chennai, India, *Hydrol. Earth Syst. Sci.*, *19*, 785–901.

Srinivasan, V., E. Lambin, S. M. Gorelick, B. 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 Resour. Res.*, *48*, W10516, doi:10.1029/2011WR011087.

Stepp, J. R., E. C. Jones, M. Pavao-Zuckerman, D. Casagrande, and R. K. Zarger (2003), Remarkable properties of human ecosystems, *Conserv. Ecol.*, *7*(3), 11.

Troy, T. J., M. Konar, V. Srinivasan, and S. Thompson (2015), Moving socio-hydrology forward: A synthesis across studies, *Hydrol. Earth Syst. Sci. Discuss.*, *12*, 3319–3348, doi:10.5194/hessd-12-3319-2015.

van Emmerik, T. H. M., Z. Li, M. Sivapalan, S. Pande, J. Kandasamy, H. H. G. Savenije, A. Chanan, and S. Vigneswaran (2014), Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River basin, Australia, *Hydrol. Earth Syst. Sci.*, *18*(10), 4239–4259, doi:10.5194/hess-18-4239-2014.

Voss, K. A., J. S. Famiglietti, M. Lo, C. de Linage, M. Rodell, and S. C. Swenson (2013), Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region, *Water Resour. Res.*, *49*, 904–914, doi:10.1002/wrcr.20078.

Wada, Y., L. P. H. van Beek, C. M. van Kempen, J. W. T. M. Reckman, S. Vasak, and M. F. P. Bierkens (2010), Global depletion of groundwater resources, *Geophys. Res. Lett.*, *37*, L20402, doi:10.1029/2010GL044571.

Walker, B., S. Carpenter, J. Anderies, N. Abel, G. Cumming, M. Janssen, L. Lebel, J. Norberg, G. D. Peterson, and R. Pritchard (2002), Resilience management in social-ecological systems: A working hypothesis for a participatory approach, *Conserv. Ecol.*, *6*(1), 14.