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# Debates—Perspectives on socio-hydrology: Changing water systems and the "tyranny of small problems"—Socio-hydrology

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**Abstract** We are well and truly in the Anthropocene. Humans can no longer be considered as mere external drivers or boundary conditions in the hydrologic systems we study. The interactions and feedbacks between human actions and water cycle dynamics on the planet, combined with the evolution of human norms/values in relation to water, are throwing up a range of emergent "big problems." Understanding and offering sustainable solutions to these "big problems" require a broadening of hydrologic science to embrace the perspectives of both social and natural scientists. The new science of socio-hydrology was introduced with this in mind, yet faces major challenges due to the wide gulf that separates the knowledge foundations and methodologies of natural and social sciences. Yet, the benefits of working together are enormous, including through adoption of natural science methods for social science problems, and vice versa. Bringing together the perspectives of both social and natural scientists dealing with water is good for hydrologic science, having the salutary effect of revitalizing it as use-inspired basic science. It is good for management too, in that the broader, holistic perspectives provided by socio-hydrology can help recognize potential "big" problems that may otherwise be unforeseen and, equally, identify potential "alternative" solutions to otherwise intractable problems.

> Organizations with narrow fields of vision become institutionally incapable of spotting where the icebergs ahead are located.
>
> *Demby* [2012]

## 1. Debating Socio-hydrology

I am delighted to join this timely debate on socio-hydrology. The starting point for me is the accompanying paper by *Di Baldassarre et al*. [2015], which addresses the issue of estimating and managing flood risk under human-induced changes in the emergent Anthropocene. The paper contrasts the traditional scenario-based approach based on assumed quasi-stationarity with a more sophisticated approach that permits analysis of the dynamic interactions and feedbacks between floods and societies. In the old paradigm, for a chosen design period, flood risk is estimated as a combination of the probability of flooding under assumed quasi-stationarity and the potential damages. In the new paradigm, however, a coupled socio-hydrology-flood model is proposed that permits exploration of the resulting coevolution of floods and societies, with a focus on estimation of emergent flood risk.

In my opinion, there are two important lessons to be learned from this paper that go beyond mere estimation of flood risk. First, the paper is an example of the broadening of the foundations of hydrologic science to accommodate the emergent dynamics resulting from the two-way coupling of social and hydrological systems, the defining feature of the new discipline of socio-hydrology [*Sivapalan et al*., 2012, 2014]. Second, it is the richness of the resulting socio-hydrologic dynamics, including possible (otherwise unimaginable) vistas about the future, in two different types of societies (e.g., green and technological), that a simple model with just three differential equations and five parameters is able to generate. In my paper, I trace the history of, and rationale for, the nascent field of socio-hydrology, put the recent modeling work of *Di Baldassarre et al*. [2015] in a broader context, and address (and debate) the concerns and criticisms that have been raised in respect of the new field in the past 3 years (and before).

**Water Management in the Murrumbidgee Basin:
Future Projection**

- Increased productivity is a given with more produce per drop (farm output $/Mega-Liter).
- New assets in the valley will appear with the primary purpose of efficiently supplying to environmental customer
- Water trading will become more efficient and sensitive to climate trends, better than stock traders in Wall Street
- There will be fewer farmers, with only the most water efficient ones surviving, the rest selling out their water rights and leaving.
- In the extreme case, (he fears that) some communities/townships could even disappear from the map.

**Figure 1.** Crystal ball projections for water management within the Murrumbidgee River Basin (courtesy: Amit Chanan).

## 2. Tyranny of Small Decisions

For me the rationale for socio-hydrology was brought home during an extended stay in Sydney, Australia, during the (northern) summer of 2011. While there I was introduced to the water management problems within the Murray-Darling River Basin, and commenced a (still ongoing) collaboration with colleagues at the University of Technology Sydney and the State Water Authority of New South Wales (NSW), focused on the Murrumbidgee River Basin, a subbasin of the Murray-Darling Basin.

Through analysis of historical data available, we traced the history of agricultural water development within the Murrumbidgee over the past 100 years, framed as a competition for water between humans and the environment. The history of water management was divided into four eras [*Kandasamy et al*., 2014]. During Era 1, the focus was exclusively on agriculture development, with little attention paid to the environment. Era 2 saw the onset of some environmental problems (e.g., salinity) and the introduction of remedial infrastructure, which did not address the root causes of these problems. During Era 3, agriculture expanded with further expansion of dams and weirs, and the resulting, increased exploitation of water and land resources contributed to widespread environmental degradation, which led to several mitigation measures in the form of policy changes, economic measures, and infrastructure development. The failure of these initiatives to reverse environmental degradation, exacerbated by the onset of a severe long-term drought in the 1990s, saw during Era 4 the implementation of a mix of solutions, including a drastic one imposed by the government in the form of a buy-back of water rights from farmers. These set in motion, by the 2000s, a downturn in all indicators of agricultural water allocation, and an upturn in water allocations (and associated infrastructure) to the environment. We characterized this long-term (emergent) dynamics as a *pendulum swing* [*Kandasamy et al*., 2014], a form of dynamics (or spiraling) that was also enunciated by *Di Baldassarre et al*. [2015] in the case of human-flood interactions.

Dr. Amit Chanan is General Manager of NSW State Water and during one of our meetings at State Water he gave an overview presentation on the water management issues within the Murrumbidgee and how his agency manages more than $6 billion worth of assets (dams, weirs, irrigation canals, etc.). By this time, I was already fully aware of the major debates raging in the community about a new water plan the government had introduced, with the farmers up in arms against the provision in the plan for the government to buy back their water rights. I was quite conscious of the difficulty of being a manager in such a politically charged atmosphere. So I was curious, and I asked him how he manages his responsibility and who was his main customer on a day-to-day basis. The answer he gave me came as a surprise. He said that the environment was his main customer and that a significant part of his team's efforts were focused on satisfying this new environmental customer. It was a surprise, because in spite of the fact that he had to deal with a highly vocal farm community, this manager of a major water utility was instead focused on catering to an apparently nonvocal stakeholder, the environment. How did this come about?

Considering the changes that have happened over the last 100 years in the basin, and given his considerable experience in managing the water resources in the State, I asked Amit Chanan to take out his "crystal ball," project to the future and tell us what he expected to see in the Murrumbidgee over the next 50 years. Key elements of Amit Chanan's "crystal ball" projections are presented in tabular form in Figure 1.

Amit Chanan's projections go beyond what normal hydrological models can predict, and beyond what traditional water resources system optimization models are programmed to predict. While they are plausible outcomes of development, hydrological science as it is presently configured cannot make such projections. The breadth and reach of his projections convinced me even more of the now familiar slogan, "hydrology is more than just the study of water" (C. Harman, personal communication, 2007).

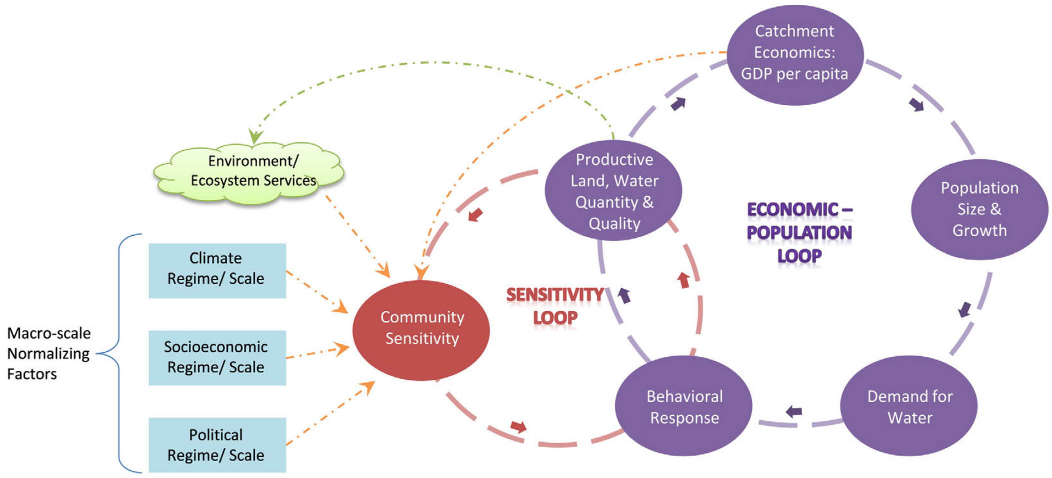


**Figure 2.** Two feedback loops, economic-population loop and environmental-sensitivity loop, and the role of community sensitivity state variable and behavioral response function (taken from *Elshafei et al*. [2014]). Community sensitivity is governed by both local factors and by regional or global climatic, socioeconomic, and political regimes.

One can be sure that the hydrology of the Murrumbidgee was well understood and well studied. The best tools were indeed being used to support water resources management. And yet, one presumes that even the best understanding and the best management tools did not recognize the long-term dynamics (i.e., pendulum swing) until after they had happened. These raise important questions for science. Is it a failure of science, if so whose science? Should we concentrate on simple (neat) problems, and leave the more complex (wicked) problems to someone else? Should not our science (hydrology, water resource system science) develop the capability to capture whatever goes into the minds of crystal ballers like Amit Chanan? Should not we grow our science so we can provide science tools that can go beyond crystal balls so managers like Amit Chanan can make better long-term strategic water management plans? (And not miss obvious "icebergs" that may be present?)

To my mind, the dynamics observed within the Murrumbidgee as a result of the competition for water between humans and the environment in an agricultural landscape, and the analysis results presented in *Di Baldassarre et al*. [2015] in respect of emergent flood risk in a growing urban landscape, draw attention to a tension between focusing on "the here and the now" as opposed to longer-term (larger scale) dynamics. Environmentalist William Odum [*Odum*, 1982] highlighted this tension in a paper titled "Environmental Degradation and the Tyranny of Small Decisions," in which he argued that "a holistic rather than reductionist perspective is needed to avoid the undesirable, cumulative effects of small decisions" (by the way the notion of the "tyranny of small decisions" was first proposed by economist Alfred E. Kahn). Odum also warned against too much focus on single-cause single-effect problems, which he called "small problems."

Murrumbidgee is not the only place in which this kind of emergent dynamics has been observed, arising from a competition between humans and the environment. I have subsequently come to learn that similar dynamics are also manifested in the Tarim Basin in Western China [*Liu et al*., 2014], Lake Toolibin catchment in Western Australia [*Elshafei et al*., 2014], and the Kissimmee Basin in Florida [*Chen et al*., 2014]. Of course, these happen to be generally "good news" stories, and need to be contrasted with the "bad news" story of the irreversible change that happened in the Aral Sea in the former Soviet Union, leading to total collapse and abandonment [*Kasperson et al*., 1995], and the developing new story of the same Aral Sea syndrome impacting Lake Urmia in Iran [*AghaKouchak et al*., 2015]. A challenging research puzzle in the research on sustainable water management is why some societies are able to successfully recover from "environmental degradation," transitioning to "successful adaptation" over decadal time scales, while others (e.g., Aral Sea, perhaps Lake Urmia) fail. It is this paradox and several others highlighted in *Sivapalan et al*. [2014], e.g., peak water paradox, improved efficiency paradox, virtual water paradox, that have provided the rationale for the launch of the new discipline of socio-hydrology, as the means to overcoming the "tyranny of small decisions," of the kind witnessed in the Murrumbidgee.

## 3. Searching for a Crystal Ball: Coupled Human-Water Systems

*Elshafei et al*. [2014] and *Liu et al*. [2014], followed by *van Emmerik et al*. [2014], attributed the pendulum swing observed in the Murrumbidgee basin in eastern Australia, Lake Toolibin basin in Western Australia and the Tarim Basin in Western China to two competing feedback loops (Figure 2). The first one is an "economic-population loop," a positive feedback loop, in which the main resources of water, land and humans are combined to produce economic gain (in the form of agricultural crops). Population growth and economic gain are the key drivers feeding into water management decisions, such as water extraction rates, land clearance rates, and the construction of storage facilities. As the per capita economic gain increases, the river basin presents an attractive lifestyle proposition, causing migration of more humans into the basin. The growing population is accompanied by higher levels of demand for water and land, by virtue of increased consumption and a growing requirement for economic development to sustain the larger community, and the positive feedback loop spirals upward, as seen in the Murrumbidgee.

The second, a negative feedback loop, is called the "environment-sensitivity loop," and reflects the reaction of the environment to the exploitation of land and water. Whereas management decisions would be reflected in a community's economic prosperity in the short term, in the longer term they filter through to water quantity and quality variables. Economic growth will continue until such time as the quantity or quality of water resources and the state of the environment begin to impede further growth through the cost of environmental degradation and reduced productivity of the land. The environmental degradation can impact farmers' actions also through the raising of increased environmental awareness by environmental lobbies, both locally and globally, which contributes to subsequent government intervention. Water use efficiency measures undertaken might temporarily extend the life or economic productivity of the system. However, in the long term, as flow continues to decrease, water quality deteriorates or land degrades, economic growth will naturally become constrained. As communities face decreasing economic prosperity and degrading natural resources, they will be compelled to act in an effort to reverse the negative threat to their overall well-being, all of which contribute to a negative stabilizing force, again as observed in the Murrumbidgee. In summary, the long-term dynamics, i.e., pendulum swing, observed in the Murrumbidgee (and other agricultural) basins are the net result of the competition between these two positive and negative feedback loops.

Even though the paper by *Di Baldassarre et al*. [2015] addresses the issue of emergent risk in relation to urban flooding, one can see an exact analogy in the drivers of the governing dynamics here to what happens in agricultural basins. Here too we have two feedback loops governing the key drivers that are in competition with each other. The first driver, called the "levee effect" relates to enhanced economic and urban development in the floodplain immediately after levees are built or raised. Flood control structures tend to promote an increase of the exposure and vulnerability of societies, leading to increasing flood risk. The second driver, called the "adaptation effect," is a result of a lowering of the impacts of a flood event when it occurs shortly after a similar flood, from enhanced coping and adaptation capacities gained following previous flood events, including early warning systems, community engagement to raise awareness, and changes to land use planning. These examples lead me to think generally that emergent long-term dynamics resulting from human-nature interactions can be framed in terms of competition between two feedback loops (called the *Taiji-Tire Model* by *Liu et al*. [2014]) that represent a *human productive force* and an *environmental restorative force*. It appears that the dynamics we highlight through these examples is similar to the hierarchies and adaptive cycles (and the notion of panarchy) in the dynamics of socio-ecological systems [*Hollings*, 2001].

If Murrumbidgee is an example of a society changing the hydrology to respond to changing social norms, the urban flooding problem here is an example of changing perceptions of risk in society. However, these are not the only examples of complex dynamics emerging from human-water feedbacks. There is the example of the efficiency paradox witnessed in Xingjiang Province in Western China [*Zhang et al*., 2014], where increased water use efficiency through improved technology (e.g., mulching) and the securing of additional freshwater resources only encouraged farmers to expand the land area put under irrigation, negating any gains obtained in the first place. Each of these examples presents a problem broader in scope than the kind of problems hydrologists traditionally study. I like to call them "big problems" (i.e., not single cause-single effect): they are real, they are about water, they affect real people and yet hydrology as we know it is just one (but critical) component. Should we hydrologists take them on as "our" problems? If we do care about

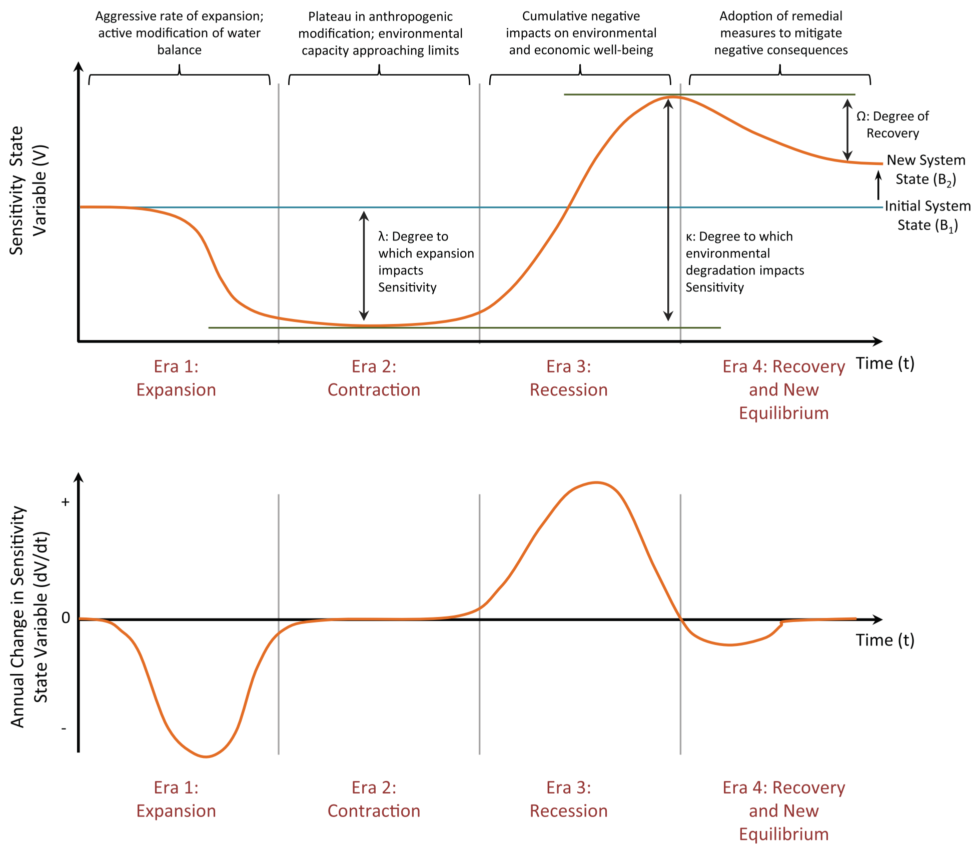


**Figure 3.** An idealized sketch showing a hypothetical trajectory over time of (a) the community sensitivity state variable (V) and (b) the rate of change of community sensitivity (dV/dt) (taken from *Elshafei et al*. [2014]).

the vitality of our science, can we afford not to? Paraphrasing from *Wood et al*. [2012], I would argue that "... there is a grand need, there are great new opportunities, and if the hydrologic community does not do it someone else will do it, albeit poorly."

## 4. Emergent Dynamics and Changing Social Values/Norms

Going back to the agricultural basins (e.g., Murrumbidgee, Tarim, Lake Toolibin, Kissimmee), the emergent dynamics observed in these basins were a reflection of the self-organization of the human-water system within given hydroclimatic and socioeconomic regimes, a result of balancing human productive forces related to human preferences for economic gain and environmental restorative forces that aim to preserve the natural environment. On the production side, the goal is to utilize water for enterprise, profit and the community's economic well-being. On the restorative side, the goal is to conserve water so as to satisfy "nature's demand" (e.g., biodiversity, wetland ecology). In a situation where nature's demand is just barely met, extreme events such as droughts could magnify these effects, triggering drastic human intervention.

Regardless of differences between the nature of the drivers in different places, the key point that needs to be remembered is that the competition between water for humans and water for the environment is ultimately mediated by humans alone, acting for themselves and acting for the environment (which cannot speak for itself). In other words, this competition is really playing out within the minds of individual human beings and within society at large, just as it is playing out in the landscape. We cannot understand, let alone make future projections of any long-term dynamics, without understanding how the issues of economic gain, environmental degradation or flood risk are playing out in society, and how societal perceptions then impact decisions in respect of human settlement, infrastructure development and environmental protection.

In the conceptual framework presented in Figure 2, taken from *Elshafei et al*. [2014], human mediation of the two competing feedback loops are captured in a *community sensitivity* state variable and a *behavioral* *response* function contained within the environment-sensitivity loop. The basic premise here is that water management decisions are driven by a community's changing social and environmental values, derived through local action and the work of farmer and environmental lobbies, which reflect the *community sensitivity* to a marginal change in one or more of the water (or associated environmental) variables. The *behavioral response* (i.e., the feedback from the human system) reflects human actions as a reaction to changes in the community sensitivity. As the community sensitivity state variable reflects the extent of a community's concern for, or awareness of, its natural environment, it follows that an increase in community sensitivity would cause behavior and management decisions to tend toward reducing the community's impact on the basin's hydrological signatures (i.e., a move toward environmental restoration). Conversely, lower-community sensitivity levels will be associated with a more aggressive response that favors manipulating available water resources to the community's economic needs (i.e., a move toward resource exploitation).

Figure 3, taken from *Elshafei et al*. [2014], illustrates hypothetically how the community sensitivity state variable might vary over time in an idealized case. It initially tracks an expansion phase during which there is a strong drive for anthropocentric resource exploitation, reflecting a sharp decline in community sensitivity levels driven by increasing economic prosperity and an aggressive rate of environmental modification. This is followed by a contraction phase characterized by a cessation in environmental modification, with economic prosperity offset by negative environmental consequences. These first two phases are part of the economic-population loop in Figure 2. They are then followed by the recession phase that experiences a sharp decline in environmental resources, accompanied by a downturn in economic prosperity linked to environmental degradation. The recession phase represents the onset of the negative feedbacks inherent in the environment-sensitivity loop in Figure 2. The final recovery and new equilibrium phase is characterized by a shift toward envirocentric management and policy.

In summary, then, the emergence of observed long-term dynamics (e.g., pendulum swing in the Murrumbidgee) can be attributed here to a change in societal norms and values [*Sivapalan et al*., 2014] in respect of the water and the environment, as highlighted by the trajectory of community sensitivity in Figure 3. One could cite many examples from the literature, not only the Murrumbidgee [*Kandasamy et al*., 2014], where this kind of behavior in both system dynamics and community sensitivity can be demonstrated: Saskatchewan River Basin in Canada [*Gober and Wheater*, 2014], Tarim River Basin in China [*Liu et al*., 2014], Lake Toolibin Basin in Western Australia [*Elshafei et al*., 2014; Y. Elshafei et al., A model of the socio-hydrologic dynamics in a semi-arid catchment: Isolating feedbacks in the coupled human-hydrology system, submitted to *Water Resources Research*, 2015]. Note also that community sensitivity is analogous to the flood memory state variable adopted by *Di Baldassarre et al*. [2013, 2015] to mediate the competition between the levee and adaptation loops for the urban flooding system.

Apart from the technical details, apart from the fact we are dealing with a complex system involving competing feedback loops, the definitions, quantification, and measurement of both community sensitivity and behavioral response, all fall within the realm of the social sciences. Their adoption here heralds a major broadening of hydrologic science. As hydrologists, are we willing (and able) to go out of our comfort zone and engage with social scientists? What does it take to bridge the wide gulf that separates social and natural sciences? How do we retain the coherence and rigor of hydrology as we broaden ourselves to tackle these "big" problems?

## 5. Socio-hydrologic Modeling: "Doing Social Science Using Natural Science Methods"

In the context of bridging the gap between social and natural sciences, the socio-hydrologic modeling effort presented in *Di Baldassarre et al*. [2013, 2015] may be characterized as an example of "doing social science by natural science methods." By way of background, I must explain the fundamental differences between social science and natural science methods. As also discussed in *Di Baldassarre et al*. [2015], the social science method typically involves community surveys, followed by statistical analysis to test hypotheses, and culminates in a narrative, a description of the state of play in a given place. Controls or cause-effect relationships, if they exist, appear implicitly in the narrative. It is not common to seek general descriptions, or seek ways to extrapolate to other places. On the other hand, the natural science method typically involves development of a concept or a hypothesis (e.g., water balance in hydrology), choosing a set of observable variables, followed by building a numerical model, its prediction tested against data to test the hypothesis. The focus is on discovering cause-effect relationships of the whole system and ultimately on achieving a generalization, including the ability to extrapolate to other places.

The paper by *Di Baldassarre et al*. [2015] represents one example of socio-hydrologic modeling, used to explore the long-term dynamics resulting from feedbacks between flooding and urban development. In this case, the dynamics were parsimoniously described by a set of three coupled nonlinear differential equations to characterize how physical, economic, political, technological, and social processes coevolve over time, punctuated by the occurrence of flooding events. In the last 3 years, a diversity of modeling approaches of this *genre* has appeared in the literature. They range from complete earth system models that capture the socio-hydrological processes in quite a lot of detail in a spatially distributed manner, to stylized models that abstract the coupled socio-hydrologic system into a small number of interconnected subsystems, and everything in between. Examples of socio-hydrologic models in this hierarchy include the System of Systems model presented in *Yaeger et al*. [2014], the stylized models presented in *Srinivasan* [2015] and *van Emmerik et al*. [2014], and the more generic model presented in *Di Baldassarre et al*. [2015].

The more realistic, detailed, and place-based models are better suited to analyzing and quantifying the socio-hydrologic interactions and feedbacks in real time in specific places [*Yaeger et al*., 2014]. They would involve substantial data collection and experimentation (e.g., detailed process modeling) to parameterize the social and hydrologic processes and the socio-hydrologic feedbacks. Stylized models simplify the systems considerably and have less power to characterize what happens in a specific place, but can be useful to serve as tools for comparative studies and toward synthesis efforts to move toward generic models applicable to a wide range of places, and toward discovering common organizing principles [*Srinivasan*, 2015; *van Emmerik et al*., 2014; *Elshafei et al*., 2014]. Agent-based models are used often by social scientists to conceptualize human-water interactions on the basis of rules generated through field surveys aimed at characterizing the behavior of human (or social) agents [e.g., *Evans and Kelley*, 2004]; such agent-based models, upon aggregation, can be used to understand emergent behavior at whole-system scale [*Magliocca et al*., 2014].

Regardless of the approaches adopted, socio-hydrologic modeling faces several conceptual and practical challenges, as outlined in the accompanying paper by *Troy et al*. [2015]. As Troy et al. explain, first and foremost, unlike in the case of traditional hydrological models, there exist no fundamental concepts (e.g., water balance) or process theories (e.g., process descriptions for infiltration, runoff generation, evaporation, etc.) let alone governing equations, to guide the development of socio-hydrological models. This means that the models will need to be data based, either empirical models or conceptual models inferred from available data. Early versions of data-driven conceptual models by *van Emmerik et al*. [2014] and *Elshafei et al*. [2014] are aimed at hypothesis generation rather than hypothesis testing [*Troy et al*., 2015]. Given the empirical basis of even conceptual socio-hydrologic models, modeling suffers from several practical limitations. Since we are focused on long-term dynamics, one requires long-term data sets that capture the covariation hydrologic (e.g., flows, irrigation area, reservoir storage, and wetland health) and social (e.g., population size, crop production, environmental awareness, and community sensitivity) systems. Considerable effort will be needed to assemble and process available data sets before modeling can proceed. Also, several of the variables cannot easily be expressed in quantitative terms, and even if they can be defined in quantitative terms, there are real challenges to measuring these in the field. The conceptualization, quantification and measurement of all variables, especially social variables, suffer from scale issues, a result of discrepancies between the scales at which they may be measured and the scales at which they are modeled. These limitations impact adversely on our ability to develop, calibrate and validate socio-hydrological models [*Palmer and Smith*, 2014]. All of these limitations have indeed come to the fore during the past 3 years. As daunting as they are, I would argue that these problems can only be overcome through intense engagement between hydrologists and social scientists; there is no short cut. In support of my argument, I quote from *Raadgever* [2009]: "Many obstacles to effective collaboration can only be removed from the path by intensive collaboration."

## 6. Uses of Socio-hydrologic Models: Moving From the Specific to the General

There can be several motivations behind the development of socio-hydrologic models. First and foremost, modeling itself constitutes a rigorous intellectual exercise to help us to understand and characterize system transitions through mimicking observations, and thus gain insights into the potential hydroclimatic, environmental, and socioeconomic drivers behind these transitions.

However, as in any other environmental or earth science, including hydrology, the modeling need not be limited to (and is never about) just mimicking the observations. The ultimate goal, which modeling can assist with, is to be able develop generalized or transferable understanding of socio-hydrologic system dynamics that goes beyond a single place. The generalization is achieved through comparative analysis and synthesis efforts that seek similarity or order, in the otherwise apparent dissimilarity or disorder found in the observations. As we progress with the modeling of individual places, and begin to find common ground between these, they will contribute to the development of more generic models for particular types of problems.

In the case of urban flooding, the model presented in *Di Baldassarre et al*. [2015] is an example of a generic model, even though, to its disadvantage it was not developed on the basis of place-based observations. Nevertheless, the results presented in *Di Baldassarre et al*. [2015] highlight the power of such models to make general statements about emergent flood risk. For example, Di Baldassarre et al. showed with the use of their coupled model that flood-poor periods can be more dangerous for societies than flood-rich periods because they lower the collective memory of flooding and therefore reduce societal resilience. They also showed that green societies have greater resilience to flooding and tend to be less affected by increasing flood frequency than technological societies. In this way, the model has been used to generate plausible hypotheses that can now be tested through careful assembly of appropriate data. In the same way, there is every expectation that in the near future we can develop more generic models for agricultural basins building on similarities between several current place-based models [e.g., *van Emmerik et al*., 2014; *Liu et al*., 2015; Elshafei et al., submitted manuscript, 2015] and use these generic models to discover natural scale dependencies that cannot be seen otherwise [see, e.g., *Di Baldassarre et al*., 2015; *Viglione et al*., 2014], and look for underlying organizing principles. An example of an organizing principle is the Environmental Kuznets Curve [*Tisdell*, 2001], which governs the macroscale socioeconomic controls on community sensitivity to the environment.

One of the potential uses of place-based socio-hydrologic models is decadal to century-scale predictions. However, this presents major difficulties, due to several reasons [*Thompson et al*., 2013]: (i) uncertainty of model structure and model parameterizations, (ii) inability to capture the highly adaptive and the (sometimes or apparent) irrational behavior of humans, and (iii) inherent lack of predictability and uncertainty due to the highly nonlinear nature of the coupled socio-hydrologic systems, e.g., strong dependence on initial conditions. Therefore, application of these models, to be meaningful, needs explicit treatment of uncertainty through the use of stochastic methods. Through quasi-analytical derivations (in the case of simple models) or Monte Carlo simulations, the models can be employed to generate possible "futures" and associated probabilities, which can be very useful to governments and large multilateral organizations for making strategic decisions. Although the broadening to accommodate human-water system feedbacks contribute increased uncertainty, it offers the advantage that it can potentially reveal the onset of unanticipated problems or black swan events [*Kumar*, 2011], or solutions to otherwise insurmountable problems, through the use of these future "projections." Indeed, in the accompanying paper, *Gobe and Wheater* [2015] suggest, inter alia, that ". . .in the hands of imaginative practitioners" socio-hydrologic modeling "can be a powerful tool for climate adaptation, land use planning and floodplain management."

For example, for a region dominated by irrigated agriculture and suffering environmental degradation, one wonders if dry-land (rain-fed) agriculture falls out as a probable outcome from the implementation of a socio-hydrologic model of sufficient breadth, enabling decision makers to anticipate this as a potential management solution without being forced into it by circumstances. This is another reason for the broadening of the science that is proposed here, i.e., as the means to "spot the icebergs" and to overcome hydrology's own "diversity handicap."

## 7. Broadening the Scope of Hydrologic Science: Socio-hydrology

The story so far has been about "big problems" that arise in the Anthropocene, a consequence of emergent dynamics arising from coupled human-water system feedbacks, and the inadequacy of solutions ("small decisions") generated through narrow disciplinary perspectives, i.e., hydrology's "diversity handicap."

Understanding these complex systems and utilizing this understanding toward sustainable management requires a broadening of hydrologic science to embrace the perspectives of both social and natural scientists, with its attendant challenges. This was also the rationale behind the launch of the field of socio-hydrology and the new global, decadal initiative of the International Association of the Hydrological Sciences, called *Panta Rhei: Change in Hydrology and Society* [*Montanari et al*., 2013].

However, this is not to suggest that this is a new development in hydrology and water resources. In fact, this idea was very much in the minds of the founders of the *Water Resources Research* 50 years ago, who had the wisdom and the foresight to appoint a natural scientist (hydrologist) and a social scientist to be joint editors of the journal. The same is true in respect of the work of *Di Baldassarre et al*. [2015] on human-flood interactions: *Gober and Wheater* [2015] cite geographer Gilbert F. White who, as far back as 1945, acknowledged that “humans interact with the environment to mitigate or enhance the impacts of extreme hydrological events” [*White*, 1945]. In contrast, *Loucks* [2015] relates his experience from the 1990s when, in spite of this enlightened beginning, “prominent hydrologists resisted and objected to any inclusion of economic or social components linked to hydrologic processes”: in my opinion, this may have temporarily set back the growth of hydrology, which socio-hydrology is now helping to rectify.

In any case, the importance of such broadening efforts is not restricted to hydrology alone, and has been recognized more widely as being essential to tackle some of the most difficult “big problems” facing humanity. For example, under the guidance of Pope Francis, the Pontifical Academy has recently brought together leading natural and social scientists and has come out with a Pontifical Academy Declaration [*Pontifical Academy of Sciences*, 2014], which states inter alia: “Humanity’s relationship with Nature needs to be undertaken by cooperative, collective action at all levels – local, regional, and global. . . . That requires a collaborative effort of natural and social scientists.”

Any time such a broadening involves bridging two fields, as poles apart as natural sciences and the social sciences are, one should expect some negative reaction. Natural scientists can be expected to complain that we are contributing to an unacceptable “softening” of the science. Social scientists can be expected to complain that we are contributing to an unwarranted “hardening” of the science. Socio-hydrology is no exception to such reactions, in spite of the great strides made in the past 3 years. Socio-hydrology will continue to face criticism until both disciplines decide that it contributes to the enrichment of the respective disciplines, and practice of the new field will result in measurable societal benefits. We can take heart from *Dunne* [1998], who said inter alia: “Developing realistic integrative theories about large-scale complex processes, even if they are coarse grained, would allow hydrologic scientists to focus on research targets that are of broad significance.” Socio-hydrologic modeling, of the kind highlighted by *Di Baldassarre et al*. [2015], represents a merging of the traditions of both disciplines, and exemplifies the best that is yet to come in the future of socio-hydrology.

This is precisely why I am in socio-hydrology. I believe socio-hydrology can revitalize hydrology, in the same way as ecohydrology helped revitalize hydrology by introducing ecological principles to capture the role of vegetation in catchment water balances. Likewise, socio-hydrology can be good for social sciences through introducing natural science methods, in the same way as ecohydrology introduced physical/hydrological approaches to the study of vegetation patterns and behavior in ecology. Socio-hydrology can also be good for water resources management in that the broader, holistic perspectives provided by socio-hydrology can help recognize potential problems that may otherwise be unforeseen and similarly identify potential solutions to otherwise intractable problems.

## 8. Conclusions

As I come to the end of this article, I cannot resist returning to a previous debate in this journal on the “future of hydrological sciences.” I find myself in agreement with *Lall* [2014] about the need for a broadening of hydrologic science to address the water problems of the emergent Anthropocene. However, both of us come to this conclusion for different reasons, Lall emphasizing the climate sciences to connect people and places, whereas I emphasize the social sciences to do the same. These two broad visions can, and should, be reconciled. I also agree wholeheartedly with *Lall* [2014] about the fragmented nature of hydrologic research and the diminishing returns in going after fine detail in niche areas.

Looking forward to the next 25 years, not merely as a continuation of the past, I cannot imagine that the hydrologists of the next generation will be motivated by such "small problems" as perfecting the latest infiltration equation, measuring flow in a macropore on a remote island, or adopting the latest computer science technique to fit a hydrograph, when they can put their creative minds toward understanding the rich symphony being played out on the Earth's surface through human interactions with the water cycle(s), in all their glory and complexity [see also *Dunne*, 1998]. To overcome the tyranny of "small problems," as *Odum* [1982] put it, we might follow his own dictum, which states, inter alia: "Scientists, no matter how reductionist their research, should be able to understand and predict how their specialty fits into whole-system processes." The visions articulated in this paper and in *Lall* [2014] and *Wood et al*. [2012], taken together, force us hydrologists to deal with "big problems" of the future (some not even imaginable now) that are at once complex, grand and practical. Pursuing them while adhering to the principles of use-inspired basic science [*Stokes*, 1997], enabled by socio-hydrology, can help us to maintain coherence, retain the rigor and raise the excitement of hydrologic science.

## 9. Post Script

I am in broad agreement with the accompanying commentaries by *Loucks* [2015], *Gober and Wheater* [2015], and *Troy et al*. [2015]. Loucks queries as to what difference socio-hydrology (including modeling) can make to improved water management policies and practices. Both *Loucks* [2015] and *Gober and Wheater* [2015] argue that socio-hydrologic modeling of the sort presented by *Di Baldassarre et al*. [2015], *Elshafei et al*. [2014], and Elshafei (submitted manuscript, 2015) must be underpinned by empirical work with the involvement of stakeholders to characterize human responses to hydrology, in order to parameterize notions such as social memory or community sensitivity. *Gober and Wheater* [2015] argue that social memory (or community sensitivity) does not, adequately capture the social processes by which public perceptions are translated into policy action, and that there needs to be a broader conceptualization that includes a knowledge translation component to accommodate how scientific results are communicated to decision makers. *Troy et al*. [2015] critically review the socio-hydrologic models developed to date in terms of generality, precision, and realism, and suggest that the models must graduate from creative data analyses aimed at hypothesis generation to become formal quantitative tools that can be used for hypothesis testing and for general advancement of the foundations of socio-hydrology. Each of the commentaries is enlightening in a different way, and collectively they provide broader perspectives of socio-hydrology, and help to enrich it further.

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