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- Coevolutionary view of hydrologic systems with coupled natural and social processes
- Time scale interactions lead to emergent phenomena, such as tipping points
- Coevolutionary system models assist with strategic management over long time scales

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Time scale interactions and the coevolution of humans and water

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Abstract We present a coevolutionary view of hydrologic systems, revolving around feedbacks between environmental and social processes operating across different time scales. This brings to the fore an emphasis on emergent phenomena in changing water systems, such as the levee effect, adaptation to change, system lock-in, and system collapse due to resource depletion. Changing human values play a key role in the emergence of these phenomena and should therefore be considered as internal to the system. Guidance is provided for the framing and modeling of these phenomena to test alternative hypotheses about how they arose. A plurality of coevolutionary models, from stylized to comprehensive system-of-system models, may assist strategic water management for long time scales through facilitating stakeholder participation, exploring the possibility space of alternative futures, and helping to synthesize the observed dynamics in a wide range of case studies. Future research opportunities lie in exploring emergent phenomena arising from time scale interactions through historical, comparative, and process studies of human-water feedbacks.

1. Introduction

Space and time dependence of hydrological processes has been a common theme in the evolution of hydrologic science. For a little more than the first half of the twentieth century, hydrology was dominated by approaches that treated catchments as lumped systems or black boxes, with an explicit focus on time. Much of Robert Horton's celebrated work had a focus on time dependence [e.g., *Horton*, 1933]. Systems approaches (e.g., unit hydrograph theory [*Dooge*, 1955]) characterized the lumped catchment response as a function of time but at the event scale. Stochastic time series approaches and early conceptual watershed models explicitly recognized time dependency of catchment responses from seasonal to multi-year time scales [*Yevjevich*, 1972; *Crawford and Linsley*, 1966].

Soon after the launch of *Water Resources Research* in 1965, new methodological opportunities emerged: digital computers and new measurement technologies. There was clear enthusiasm for a new era that would replace empirical, lumped approaches by spatially distributed physically based descriptions of the hydrological system as epitomized by Freeze and Harlan's 1969 model blueprint [*Freeze and Harlan*, 1969]. The new paradigm aimed at explicitly resolving space (e.g., the SHE model [*Abbott et al.*, 1986]). Although scale issues permeated the debate on physically based distributed modeling for decades [*Beven*, 1989; *Kalma and Sivapalan*, 1995; *Blöschl et al.*, 1997], the general approach appeared viable, in particular, as spatial data (e.g., remote sensing, digital terrain data) became available, leading to new types of models (e.g., TOPMODEL [*Beven and Kirkby*, 1979]) and new avenues for the testing of such models [*Grayson and Blöschl*, 2000]. A logical extension was the integration of a range of environmental processes into such models, including chemical, erosional, and biological processes and coupling with the atmosphere [e.g., *Kumar et al.*, 2009; *Therrien et al.*, 2010]. However, as the focus shifted to capturing spatial heterogeneity and improved process resolution [*Wood et al.*, 2011], the treatment of time was mostly limited to whatever time variability was in the climate inputs.

With the rapid changes brought about by human impacts on the hydrologic cycle, there is now an increasing need to refocus on time dependency [*Wagener et al.*, 2010]. The time horizon over which strategic or planning decisions are made is also becoming longer [*Montanari et al.*, 2013] which adds to the urgency to bring time

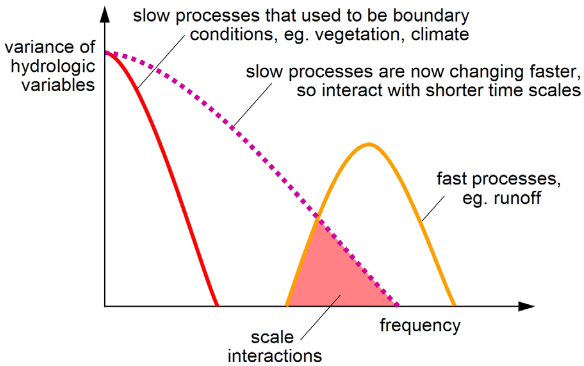

Figure 1. Schematic power spectrum of the temporal variability of hydrological processes: with the rapid changes brought about by human impacts on the hydrologic cycle separating the slowly varying boundary conditions of the Earth System from the fast varying hydrological processes may no longer be appropriate.

back to the center stage. In the past, component parts of the hydrologic system (e.g., climate, vegetation, soils, topography etc.) were changing slowly in comparison to the time scales of hydrologic processes and those of human decision making. Treating them as fixed boundary conditions was therefore often a reasonable assumption. However, under the new circumstances, separating the slowly varying boundary conditions of the Earth System from the fast varying hydrological processes may no longer be appropriate [*Thompson et al.*, 2013]. This notion is illustrated schematically by the power spectrum of hydrological processes presented in Figure 1. While, in the past, slow and fast processes could be addressed separately (by assuming a separation of scales), in order for hydrologists to predict over long time horizons relevant to societal change, the time scale interactions need to be explicitly addressed (Figure 1).

This paper explores how time scale interactions of hydrological processes can be conceptualized within the context of the coevolution of hydrological systems and societal development. In this context, we will specifically discuss the interplay of hydrological and social processes and give examples of the framing and modeling of real-world problems. The paper concludes with an appraisal of socio-hydrologic modeling to assist with strategic water management at decadal to century time scales, complementing the significant advances that have been made to water resources system analysis in the last five decades [e.g., *Loucks et al*., 2005; *Brown et al*., 2015].

2. The Nature of Coevolutionary Hydrological Systems (Without Humans)

2.1. Evolution

Hydrological processes inherently operate over many time scales. Consider meander formation. Starting with a straight channel, any kind of obstruction in the river bed, such as rocks, will introduce small disturbances in the stream geometry which, in turn, result in cross currents along the floor of the channel which sweep eroded material toward the inside of the bend and accelerate erosion on the outside, leading to meanders. As their amplitudes increase, so do the cross currents and the erosion, which again increases the amplitudes [*Ikeda and Parker*, 1989; *Scheidegger*, 2004]. There are two time scales involved here, those of the fast erosive processes, $x(t)$, and the slow changes in the river morphology, $X(t)$. The interactions between these two process time scales make the streambed evolve (Figure 2a).

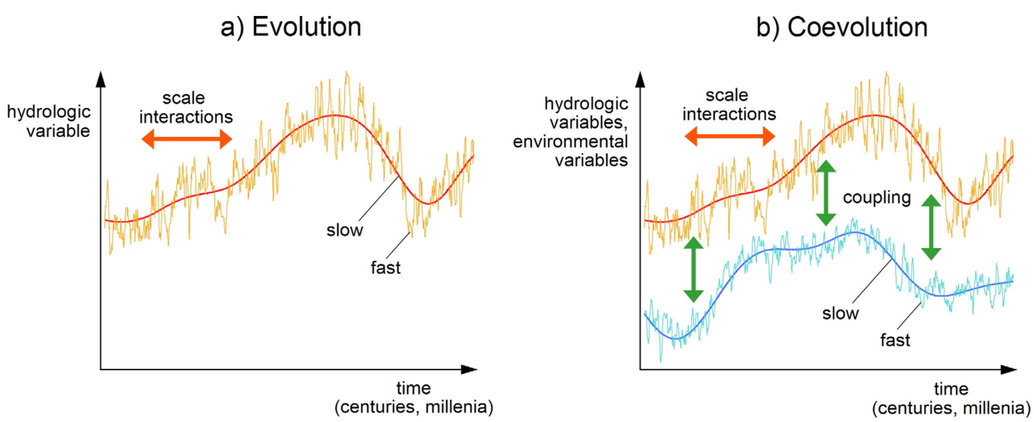

Figure 2. Schematic of (a) evolution, i.e., the interactions of slow and fast processes, and (b) coevolution, the interaction of a number of slow processes in addition to fast processes. (a) Redrawn from *Perdigão and Blöschl* [2014].

2.2. Coevolution

Hydrological systems often involve more than one slow variable in addition to fast variables. Flood formation is coupled with event-scale precipitation and seasonal soil moisture as well as with soil evolution, vegetation evolution, landscape evolution, and climate evolution over centuries to millennia [*Gaál et al.*, 2012]. Groundwater flow is coupled to the longer-term processes of subsurface formation [*Wendebourg and Harbaugh*, 1996] and landscape evolution, in addition to climate controls. The slow processes such as geology, X(t), and the topography, $Y(t)$, evolve together, and are dependent on each other and on fast processes such as runoff, $x(t)$ (Figure 2b).

The term "coevolution" was coined in the field of biology to describe the simultaneous adaptation by closely interacting animal or plant populations, each of which exerts a strong selective force on the other [*Ehrlich and Raven*, 1964]. Since then the term has been adopted by other fields, and is often related to adaptive interactions between processes drawn from different disciplines. These include coupled, evolutionary processes of climate, tectonics, and topography [*Whipple et al.*, 1999; *Reiners et al.*, 2003], climate and vegetation [*Zeng and Neelin*, 2000; *Oyama and Nobre*, 2003], and landscapes and biota [*Marston*, 2010; *Reinhardt et al.*, 2010; *Corenblit et al.*, 2008, 2011; *Porder*, 2014]. In all of these process interactions, water plays an important role. In hydrology too, the notion of coevolution has recently sparked extensive research activities in the form of both detailed observations and modeling [*Tucker et al.*, 2001; *Band and Tague*, 2005; *Paola et al.*, 2006; *Saco and Moreno-de las Heras*, 2013; *Pelletier et al.*, 2013; *Troch et al.*, 2015].

2.3. Dynamical Systems and Slow-Fast Equations

The most common way of representing coevolutionary processes mathematically is the dynamical systems concept [e.g., *Hofbauer and Sigmund*, 1988; *Robinson*, 1995]. The concept assumes that the change in the state of a system with time is a function of the state at the same time, and future states follow deterministically from the current state. A coevolutionary dynamical system could be simply written as:

$$\text{Fast:} \quad \varepsilon\frac{dx}{dt}=f(x,X:\Theta) \tag{1a}$$

$$\text{Slow:} \quad \frac{dX}{dt}=g(x,X,Y:\Phi) \tag{1b}$$

$$\text{Coupled slow:} \quad \frac{dY}{dt}=h(X,Y:\Psi) \tag{1c}$$

where x is the variable that varies on a fast time scale, X is the same variable but varying at a slow time scale, and Y is a different variable that is coupled to X and also operates at a slow time scale. For example, x, X, and Y could relate to the orange, red, and dark blue lines in Figure 2b. The coupling between equations (1a) and (1b) represents time scale interactions, and the coupling between equations (1b) and (1c) represents the coevolutionary process. $\Theta, \Phi,$ and Ψ are the parameter vectors of this coupled system. Obviously, the rate of change of the fast system (equation (1a)) is larger than that of the slow system (equation (1b)). To highlight the difference in the rates, following the idea of scale analysis [*Charney*, 1948; *Price*, 1986], it is usual to add a parameter ε ($\varepsilon \ll 1$) to equation (1a) which is selected in a way that the functions f and g are of similar order of magnitude [*Berglund and Gentz*, 2006]. ε is then the ratio of the small and large time scales. For example, order-of-magnitude time scales for geomorphologic and ecological processes for the particular case of the North Carolina Coastal Plain are given by *Phillips* [1995]. For time scales of hydrological processes, see *Skøien et al.* [2003].

2.4. Characteristics of Coevolutionary Systems

Slow-fast systems as in equation (1) have been studied for a long time in different fields [see e.g., *Kuehn*, 2015] although they have received little attention in hydrology. Slow-fast systems represent feedbacks, between different time scales and between different variables. Positive (or benefitting) feedbacks between, say, x and Y would occur if x increases with increasing Y and vice versa, which increases any fluctuations. For example, surface runoff x may enhance land surface change Y, which in turn enhances surface runoff x through gully formation. Conversely, a negative (or antagonistic) feedback between x and Y would occur if Y decreases with increasing x. For example, soil moisture Y decreases with evaporation x from the land surface, but evaporation increases with soil moisture. These feedbacks are encoded in the functions f, g, and h used in the example of equation (1).

Given mathematical tractability, the system characteristics can be understood by inspection of the equations without resorting to simulations. One important characteristic of dynamical systems are equilibrium points at which the state variables do not change with time, i.e., the temporal derivatives on the left-hand side of the equations vanish. These equilibrium points can be classified into stable (either stable equilibria or stable periodic), unstable, and saddle points, depending on the signs of the eigenvalues of the linearized equations about the equilibria.

To illustrate the stability characteristics, we present a simple case of equation (1) which represents an idealized form of coevolution of runoff and soil depth in an agricultural field:

$$\text{Fast:} \qquad \varepsilon \frac{dx}{dt} = ax + bY + \sigma_x \tag{2a}$$

$$\text{Slow:} \qquad \frac{dY}{dt} = cx + dY + \sigma_Y \tag{2b}$$

where the variables *x* and *Y* are the runoff deviations from the mean and soil depth deviations from the mean, respectively, *a*, *b*, *c*, *d* are parameters, and σ_x and σ_Y, are exogenous (external) random variables, representing rainfall variability and landslips, respectively. The processes involve runoff eroding the soil (equation (2b)), and the soil dampening runoff variability due to its storage capacity (equation (2a)). There is therefore a feedback between runoff and soil depth.

The chosen parameters are summarized in Table A1. The relaxation times for runoff and soil depths are 1 and 1000 years, respectively. For clarity, the time scale separation ε is used which brings the parameters to a similar order of magnitude. Parameter *c* represents the erosivity. Two cases are considered, the first where a cover crop is planted during the rainy season to minimize soil erosion (i.e., inclusion of soil protection), and the second case without soil protection, which increases the erosivity by a factor of 100. The example presented is of course highly idealized, but it does demonstrate the value of the dynamical systems approach to simulate coevolutionary processes in real-world situations. For example, parameter *a* could be obtained from time series analysis of runoff data as it is related to the autocorrelation function, *b* from comparative studies of catchments or hillslopes with different soil depths, *c* from field experiments (erosion plots), and *d* from analysis of the age of soil layers.

Figure 3 illustrates the dynamics of this coupled system for one realization. As can be seen, in the case with soil protection, the system remains stable, while in the case without soil protection, runoff increases dramatically and the soil is completely eroded away at some point in time. The phase diagrams illustrate the negative feedbacks between runoff and soil depth as reflected by the negative correlations.

The stability of the dynamic system can be examined very easily. Since the equations are linear, the eigenvalues of the coefficient matrix λ_1 and λ_2 directly give the stability properties. For the chosen parameters, for the case with protection $\lambda_1 = -0.0009$, $\lambda_2 = -1.0001$, i.e., both eigenvalues are negative, and therefore the system is stable. For the case without protection, $\lambda_1 = 0.0089$, $\lambda_2 = -1.0099$, i.e., one eigenvalue is positive, one negative, therefore the system is unstable with a saddle. In situations where parameters *a*, *b*, *c*, and *d* change with time, eigenvalues also change and getting the eigenvalue λ_1 close to 0 could be indicative of early-warning of collapse [*Scheffer et al*., 2012]. We will return to the issue of early-warning in more detail later in section 3.2.

If two stable states exist, then the (bistable) system may switch between the two states, leading to abrupt shifts (or critical transitions) in the regime [*Scheffer*, 2009; *Kuehn*, 2011]. An example of a bistable system (although not necessarily involving coevolution) is the interaction of transpiration and saline groundwater, as proposed by *Peterson et al*. [2009]. As the water table approaches the surface, transpiration is reduced through a reduction in plant leaf area due to increased salinity in the root zone; and as the water table drops to great depths, the transpiration is also reduced due to the inability of plant roots to take up water. Conceptually, such a bistable system may be represented by a water balance equation of the form:

$$\frac{dS}{dt} = P - \alpha \cdot z \cdot (1 - z) \tag{2}$$

where variables *S* and *z* are, respectively, soil water storage and depth to the water table, and precipitation *P* and α are parameters. The product on the right-hand side represents transpiration. The system has two

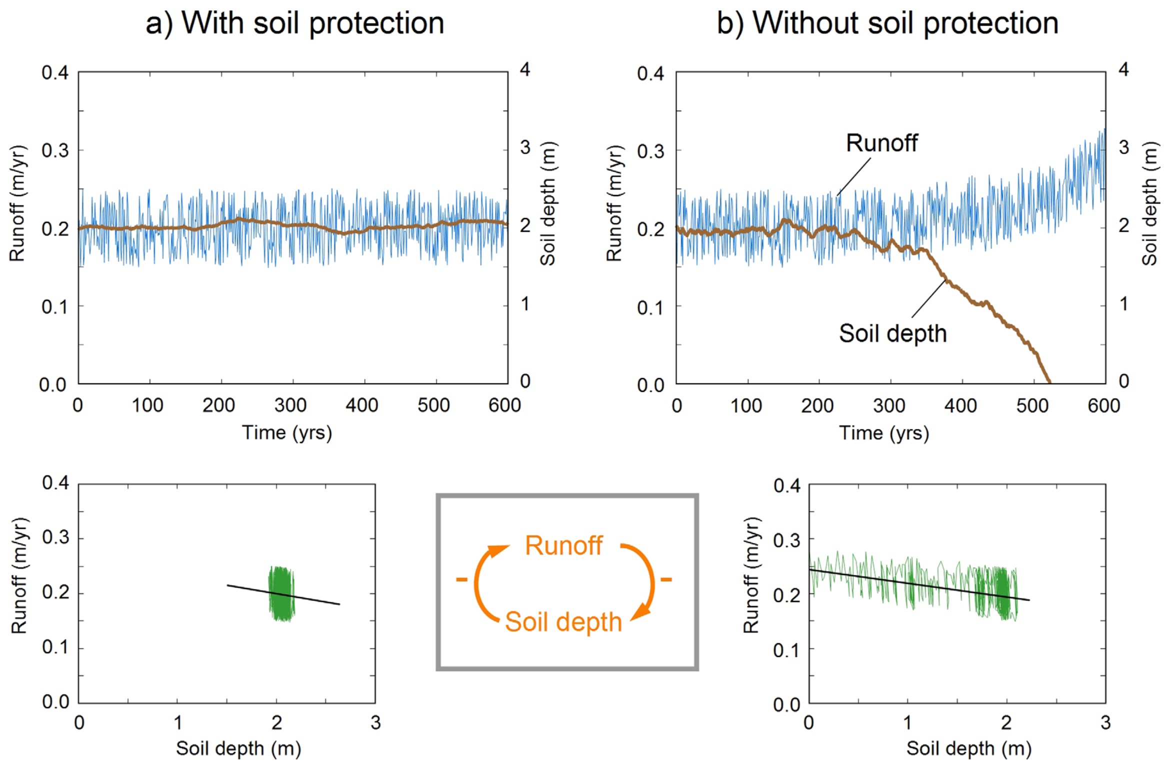

Figure 3. Coevolution of runoff and soil depth in a hypothetical landscape modeled by a coupled linear system of equations: (a) landscape with soil protection, e.g., agriculture with cover crops, and (b) landscape without soil protection. (top) Example realizations; (bottom) phase diagrams. Black lines highlight negative dependence of soil depth and runoff. The parameters used to generate these simulations are summarized in Table A1.

equilibrium points, as reflected by the two real roots of z when setting the left-hand side of equation (2) to 0, for suitable values of P and α. One equilibrium point represents a low groundwater table and functioning vegetation, while the other a high water table with little or no vegetation. Fluctuations in precipitation may then trigger shifts between the regimes over time [*Peterson et al.*, 2009].

The regime shift is an emergent behavior where new dynamics arise through the interactions of the variables at smaller or faster scales. Another example of emergent behavior is meander formation which is neither built into the equations of surface water motion nor into those of sediment transport, yet models that couple the two may produce macroscale patterns such as meanders or braiding branches [*Hooke*, 2003]. Another example is the formation of vegetation patterns in landscapes which *Saco and Moreno-de las Heras* [2013] studied through simulations with four coupled equations:

$$\text{Flow (fast)}: \quad \varepsilon_1 \frac{\partial h}{\partial t} = f_1(\nabla h, h, R, P : \Theta) \tag{4a}$$

$$\text{Soil Moisture (fast)}: \quad \varepsilon_2 \frac{\partial m}{\partial t} = f_2(h, m, P : \Phi) \tag{4b}$$

$$\text{Biomass (slow)}: \quad \varepsilon_3 \frac{\partial P}{\partial t} = g_1(m, P, \nabla^2 P : \Psi) \tag{4c}$$

$$\text{Topography (very slow)}: \quad \frac{\partial Z}{\partial t} = g_2(m, P, \nabla^2 P : \Omega) \tag{4d}$$

where the variables h, m, P, and Z are overland flow depth, soil moisture, biomass, and topographic elevation, respectively, R is rainfall, and Θ, Φ, Ψ, and Ω are associated parameter vectors. ε_1, ε_2, and ε_3 are of the order of 10^{-7}, 10^{-5}, and 10^{-2}, respectively. The equations involve the coupling of fast processes (flow and soil moisture) and slow and very slow processes (biomass and land surface elevation). Space is invoked for the movement of water, biomass (seed), and sediment in the downslope direction. Similar to river plan forms such as meanders and braiding, the vegetation patterns that emerge from these interactions exhibit a rich diversity depending on slope, erodibility (Figure 4), and other system characteristics.

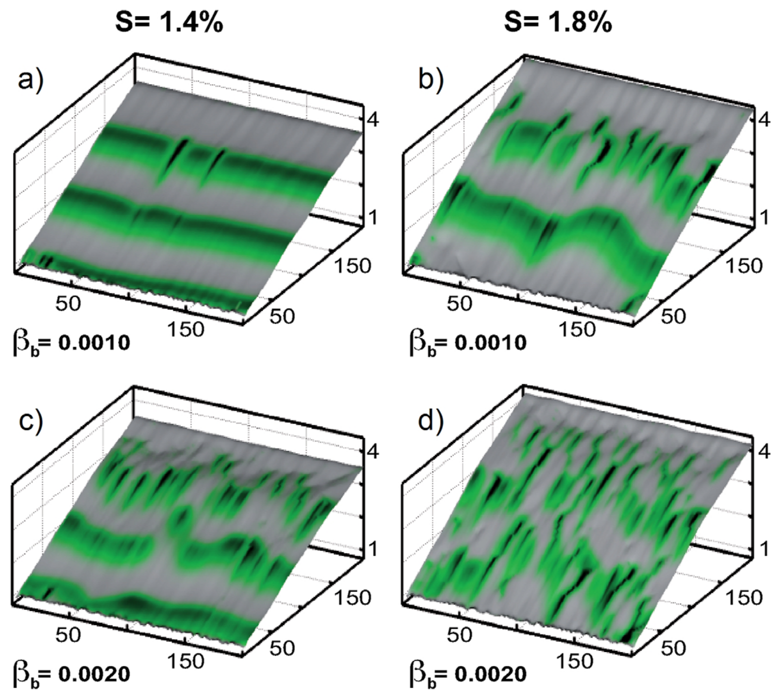

Figure 4. Emergent vegetation patterns simulated by a coupled landform—vegetation model after 1000 years. Biomass density is shown in green. Left and right columns correspond to low and high slopes ($S = 1.4\%$ and 1.8%), top and bottom columns correspond to low and high erodibility ($\beta = 0.001$ and 0.002). Taken from *Saco and Moreno-de las Heras* [2013].

2.5. Space-Time Connections and Legacy Effects

The significance of emergent patterns such as those in Figure 4 is that they can be seen as legacy effects, the spatial signatures left behind from the history of coevolution of Earth system processes. As legacy effects, they can be used to generate insights into the history of coevolutionary processes that may have produced them.

Geomorphology has a long history of interpreting landscape features that have been left behind by coevolutionary landscape processes. Even from the topography alone, former mass movements can be inferred and this can be further refined if more information on the subsurface is available [*Rhoads and Thorn*, 1996]. Similarly, the patterns left behind by coupled ecological-soil-geomorphic processes can be interpreted to infer the dynamic characteristics of the system that generated these patterns [*Monger et al*., 2015]. However, our ability to make inferences from an observed pattern is constrained by historical contingency where a number of historical events over time may have combined together to produce, and have their imprint on, that pattern [*Phillips*, 2001; *Beven*, 2015].

Ideally, it would be useful to have direct observations of how these patterns change over time, e.g., through historical photography or remote sensing. However, such observations are not usually available over century to millennia time scales. For longer time scales, indirect methods are needed. Ecology, pedology, and geomorphology have long used the indirect method of chronosequences [*Walker et al*., 2010; *Phillips*, 2015]. A chronosequence is a set of sites that share similar attributes but are of different ages. The underlying assumption behind the method is that the coevolutionary dynamics at different sites are the same but that the starting points of the dynamics differ. For example, ecological succession and soil development in an area exposed by a retreating glacier will start at different times. The assumption of similar dynamics implies that the processes currently observed at different sites can be mapped back to history by space-for-time substitution [*Pickett*, 1989], i.e., what the younger sites look like now resemble what the older sites must have looked like centuries ago. This represents a type of "natural experiment." Analyses across environmental gradients can thus be used to learn about the coevolution of processes [*Ter Braak and Prentice*, 1988].

An application of the chronosequence idea, when age is not available or not relevant, is to look for a landscape feature, such as elevation, that can serve as a surrogate for age through the tectonic and erosive processes that led to it. Places that differ significantly in terms of elevation are then compared in terms of other codependent landscape or climate characteristics, such as soils, vegetation, precipitation, and runoff, to infer the links between all these variables and understand the coevolutionary processes.

Consider the case of flood-to-precipitation sensitivity and assume, as a first step, precipitation and floods to fluctuate as in Figure 2b, but without the long-term (slow) evolution, i.e., only the high-frequency component is present. In that case, the temporal flood-to-precipitation sensitivity obtained from, say, a 30 year record of precipitation and runoff data at one location, would be the same as the sensitivity obtained from a spatial transect of precipitation and runoff at the same time. In other words, the short record contains the same dynamics as the legacy of processes apparent in the spatial differences. However, if a long-term (slow) component is also present, as shown in Figure 2b, this is no longer the case, as the 30 year temporal record will only sample the fast processes, while the spatial transect will show the legacy effects of both the fast and slow processes, i.e.,

$$\frac{dQ}{dP_t} = \frac{\partial Q}{\partial P_s} \cdot \frac{dP_s}{dP_t} \tag{5}$$

[Perdigão and Blöschl, 2014] where P is annual precipitation, Q is annual flood peak, dQ/dP_t is the sensitivity of floods to temporal precipitation changes, $\partial Q/\partial P_s$ is the sensitivity of floods to spatial precipitation changes (observed at the present time), and dP_s/dP_t is the Jacobian that accounts for the fact that the spatial precipitation coordinates evolve with time. *Perdigão and Blöschl* [2014] introduced the concept of a coevolution index, ς, which represents the differences between the spatial (representing fast and slow) and the temporal (representing only fast) sensitivities as:

$$\frac{dP_s}{dP_t} \sim P_s^{\varsigma} \tag{6}$$

If $\varsigma=0$, there is no coevolution, i.e., only the high-frequency component is present, the Jacobian is unity, and space-for-time substitution (or trading space for time) is straightforward since the temporal and spatial sensitivities are the same. However, if $\varsigma > 0$, as is the case in coevolutionary systems, one has to account for the dependence between space and time. *Perdigão and Blöschl* [2014] estimated the coevolution index from space-time data of precipitation and runoff and used it to parameterize a dynamic model of landscape-climate coevolution:

$$\text{Fast} \qquad \frac{dP}{dt} = f(P, H, \varsigma) \tag{7a}$$

$$\text{Slow} \qquad \frac{dH}{dt} = g(P, H) \tag{7b}$$

where P is precipitation and H is catchment elevation, and in this way explained the observed flood-to-precipitation sensitivities from a process perspective.

This formulation provides a framework for linking temporal changes to spatial changes in hydrologic variables across climate gradients and gives an indication whether the catchment system has reached equilibrium condition or not. If the evolution is interrupted by external shocks, then the system will remain far from equilibrium [*Beven*, 2015] and reflected in $\varsigma > 0$, and extrapolation from space to time needs to account for the Jacobian. In the context of predictions in ungauged basins, *Blöschl et al*. [2013a] argued that catchments with a similar coevolutionary history are similar and this allows information to be transferred between gauged and ungauged basins.

3. The Nature of Coevolutionary Hydrological Systems (With Humans)

Savenije et al. [2014] present a historical account of the changing relationship between humans and water from the time of the Industrial Revolution, which represents the beginning of the Anthropocene. Clearly, with the expansion of the human footprint on the hydrological cycle, the role of humans now needs to be accommodated in the coevolution of hydrologic systems [*Wagener et al*., 2010; *Oreskes*, 2015]. From a systems perspective, an analogy has been drawn between the coevolution of species and the coevolution of societies with ecosystems and the physical environment [*Winder et al*., 2005]. "Thinking of the changes in social and environmental systems over time as a process of coevolution acknowledges that cultures affect which environmental features prove fit and that environments affect which cultural features prove fit" [*Norgaard*, 1994, p. 81].

Although such concepts have not usually been considered in traditional water resources management, there has indeed been a long tradition of considering the role of humans, typically by organizing the water resources system into four subsystems [*Loucks et al*., 2005, p. 645]:

1. The natural resources system involving streams, rivers, lakes, and aquifer in the context of all the processes discussed in the previous section;
2. The infrastructure system, such as canals, reservoirs, wells, and pumping plants (including their operation rules) associated with technology;
3. The socioeconomic system related to water-using and water-related human activities;
4. The institutional system of administration, legislation, and regulation of water.

Each of these subsystems operates on a range of time (and space) scales, and in addition, they are coupled to each other via numerous positive and negative feedbacks; this makes them, collectively, a coevolutionary coupled human-nature system.

3.1. Feedbacks Between Fast and Slow Processes

It is possible to identify fast and slow processes in each of the above subsystems. The natural resources system will slowly degrade if overused through fast human processes (e.g., water extraction, land use changes) that do not allow for recovery. For example, large-scale deforestation in Western Australia for agriculture caused shifts to the water balance, leading to slowly rising water tables and extensive land and stream salinization, which contributed to a decline in agriculture and reduction of human population [*Elshafei et al*., 2015]. The infrastructure system, typically, follows a slow evolutionary path linked to innovation through the interplay between technology and society [*Geels*, 2005]. Technology includes infrastructure development to exploit water resources (e.g., irrigation technology), improved water use efficiency in agriculture, breeding of more water efficient crops, and river training and the construction of levees to protect cities from flooding. However, infrastructure develops in response to accumulated effects of human-water interactions at short time scales, e.g., frequent flooding forces people in urban settings to construct levees to protect themselves, likewise frequent water shortages in agricultural communities force people to build storage reservoirs.

In agricultural societies (as opposed to societies that depend on mining petroleum or metals), the socioeconomic system is often built on the exploitation of nature's renewable resources (e.g., soil and water) for producing economic outputs. The dynamics of the socioeconomic system is therefore intimately connected to the short-term dynamics of the resource, but in the long term, the accumulation of wealth can contribute to the growth of technology and population increase through natural growth and in-migration, both of which further expand the ability to exploit the natural resources. In developing countries, resources constitute the main input to production whereas in developed countries resources have more indirect effects modulated by consumption. International trade becomes a factor here, since there is evidence that developed countries are able to off-load a not insignificant amount of their consumption loads onto less-developed countries while importing resources from these same countries. On the other hand, overexploitation of the natural resources can cause degradation of the resource and, in the long term, lead to permanent depletion of the resource. Not properly managed, this competition can lead to catastrophic consequences, including collapse. The ancient Mayas, who settled on present-day Yucatan peninsula in southeastern Mexico, exploited the land and water resources and built a successful civilization. Interactions of short-term climate variability (e.g., droughts) and human-induced land cover changes (e.g., deforestation), combined with increasing human population and environmental degradation contributed to episodes of both collapse and recovery in the long course of their civilization [see *Dunning et al*., 2012].

The institutional (or governance) system represents a range of actors or stakeholders (e.g., state agencies and water experts, private sector and nongovernmental organizations, and citizen groups) who have to make decisions to manage the competition for water between human use (both supply and demand) in the short term and the use by the environment in the long term, to achieve sustainability [*Savenije et al*., 2014]. Indeed, as societies grew and learned to manage the competition for water for various human uses and for the environment, they developed policies, legal systems, constitutions and cultures that provided guidance to their decision making. Institutions that do poorly with keeping the collective memory alive (i.e., suffer "generational amnesia") may not be able to account for long-time scale changes.

3.2. Emergent Behavior: Collapse and Critical Transitions

Since the Harvard Water Program [*Maass et al*., 1962], linking the natural, infrastructure, socioeconomic, and institutional systems associated with water has been high on the agenda of water research. Indeed, the founding of *Water Resources Research* itself 50 years ago as an interdisciplinary journal, by surface water hydrologist Walter Langbein and environmental economist Allen Kneese, was a reflection of the importance attached to cross-disciplinary interactions. Much of the focus then was on decision making under uncertainty and comparing alternative project options by the "systems approach." While the systems approach only slowly found its way into practice [*Rogers and Fiering*, 1986], the greater pressure on water resources has in the meantime led to its much wider acceptance in the context of sustainable development [*Cai et al*., 2002; *Loucks et al*., 2005]. Given its project focus, much of the work with the "systems approach" revolved around linearization to find feasible, optimum solutions, i.e., a *normative* perspective of "what should be done" in order to solve concrete problems.

In contrast, an alternative, later line of research on coupled human and natural systems (CHANS) has been more interested in the *positive* perspective of "trying to understand what is happening and why." The objects of study were similar but the approach emphasized the many complexities of coupled system behavior, not evident when studied by social or natural scientists separately. For example, *Liu et al*. [2007a] demonstrated through examples that CHANS form complex feedback loops, involve strong nonlinearities with thresholds, and exhibit critical transitions, emergent behavior, resilience, heterogeneity, surprises, and legacy effects. These complexities have major implications for modeling human decision-making behavior [*An*, 2012], as well as for management, governance, and policy [*Liu et al*., 2007b].

Given these additional complexities, a wide range of models have been proposed that represent the coupled human-nature dynamics, including stylized models [e.g., *Anderies*, 2000], agent-based models [e.g., *Evans and Kelley* 2004; *An*, 2012; *Noel*, 2015], and comprehensive system-of-systems models [e.g., *Yaeger et al*., 2014]. Below we present an example of the complex behavior of a hypothetical coupled human-nature system, simulated by a simple, stylized model known as Wonderland [*Sanderson*, 1994; *Milik et al*., 1996]. In this model, humans exploit natural capital (resources) to produce economic output, and in the process cause pollution, which can deplete natural capital and limit long-term economic growth. The demographic (i.e., human population), economic (per capita output), and environment (natural capital) interactions in Wonderland are expressed in terms of four state variables: $x(t)$ population size, $y(t)$ per capita output, $z(t)$ quality of environment (natural capital), and $p(t)$ pollution per unit of output. Their coevolution is expressed in terms of the following four coupled, deterministic differential equations:

$$\text{Population (slow)}: \quad \frac{dx}{dt} = x\alpha(y,z) \tag{8a}$$

$$\text{Economic output (slow)}: \quad \frac{dy}{dt} = y\beta(z) \tag{8b}$$

$$\text{Natural capital (fast)}: \quad \varepsilon\frac{dz}{dt} = z(1-z)\ \chi(x,y,z,p) \tag{8c}$$

$$\text{Pollution (slow)}: \quad \frac{dp}{dt} = -\delta p \tag{8d}$$

where $\alpha(y,z)$, $\beta(z)$, and $\chi(x, y, z, p)$ are represented by specified functional relationships taken from the literature. Note that, to simplify the model, equation (8d) introduces an exogenously changing technology, which permits pollution per unit of output to decrease at a constant rate δ. Scaling analysis of the governing equations showed that environmental, economic, and demographic variables exhibit slow-fast dynamics, as represented by the parameter $\varepsilon \ll 1$ in equation (8c).

Figure 5 shows limiting behaviors of the coupled system for three different parameter combinations, presented in phase-space, which shows that the same initial conditions and years of common demographic and economic history do not imply similar futures. All of a sudden, the three scenarios—for only a change in one parameter, δ—diverge, and from the common path there is not even in an inkling beforehand of an

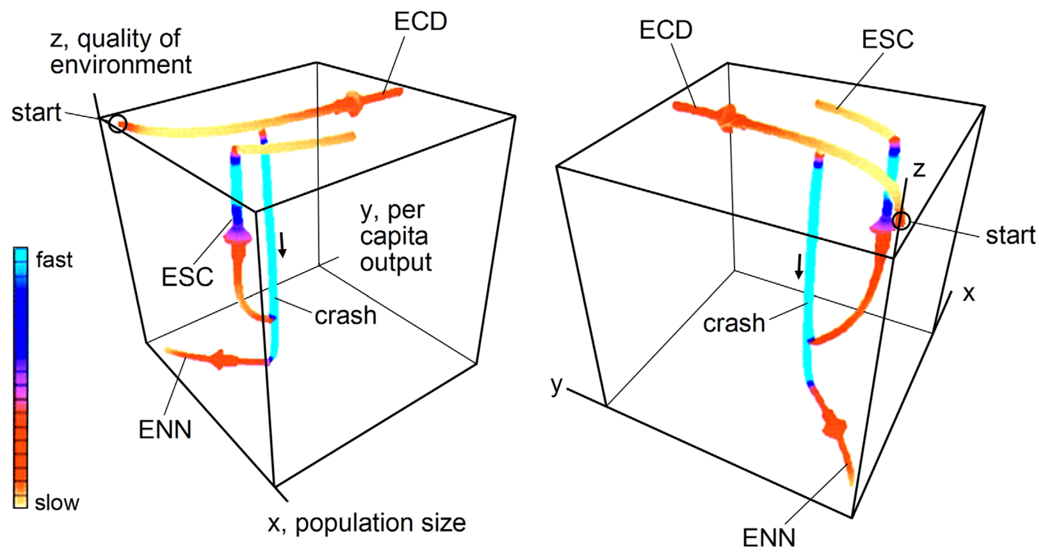

Figure 5. Phase portraits of the future of Wonderland for three scenarios: *Economist's Dream (ECD)*: pollution per unit output decreases faster than economic growth rate, population approaches zero growth, pollution flow decreases, natural capital is maintained, and future is sustainable; *Environmentalist's Nightmare (ENN):* decrease of pollution per unit output is slower than economic growth rate, pollution accumulates, natural capital depletes, population and per capita output decrease, and sustainability is endangered; *Escape from Environmental Catastrophe (ESC):* recovery from environmental catastrophe is achieved through adoption of cost-effective pollution control technology, leading to fast decline of pollution flow, leading to recovery. The two figures show the same phase portrait from different angles. Colors refer to how fast processes occur. Redrawn from *Milik et al*. [1996] and *Gröller et al*. [1996].

impending crash. Translated to the real world, this implies that humans might well live in growing prosperity for a long while even after they have crossed an environmental change "frontier." Although the model may not predict the exact date of the environmental crash, it does enable the identification of specific demographic, economic, and environmental constellations at which sustainability becomes endangered. By looking at the phase-portraits (e.g., Figure 5), we are better able to view the interactions and sensitivities than simply assessing time series of variables as is often done in traditional hydrologic modeling applications. In real-world systems (as also noted in the badlands example above), over a long period of time the parameters of such a model may themselves evolve, which would contribute to a transition between the scenarios. For example, the parameter δ could be linked to pollution dynamically, thereby introducing a negative feedback that helps to avert the tipping point.

Although sharp regime shifts may result from external shocks, the Wonderland example showed that such critical transitions can be generated internally as well, leading to "tipping points," where a minor trigger can cause a shift to a contrasting state [*Lade et al*., 2013]. By applying singular perturbation theory, the system was decomposed into slow and fast components to identify the critical border (or tipping point). A critical slowing down, when the dominant eigenvalue characterizing the rates of change around equilibrium approaches zero, and a slow recovery from small introduced perturbations, have been proposed as early-warning signs of the approach of a tipping point [*Scheffer et al*., 2009, 2012; *Kuehn*, 2015]. Frequent dam storage drought level exceedance or clustering of droughts may be examples of such early-warning signs. With the growth of the human footprint, water resources management is increasingly being asked to assess the level of human impact that may trigger abrupt transitions, regime shifts, or collapses, and equally, to assess the effort required to avoid such adverse transitions or to restore degraded systems back to "acceptable" levels of functioning [*Rockström et al*., 2014; *Hipsey et al*., 2015]. The ability to detect early-warning signs as suggested above would therefore make a fundamental difference to water resource management as it is usually practiced now, where problems are "fixed" only once they occur.

While the examples of critical transitions highlighted in this paper are appealing, these dynamics are less explored in highly complex coupled systems where more feedbacks may dampen a response and avert a critical transition. For example, the more complex the network of interactions is, the harder it may be to find critical transitions. In the socio-hydrologic context, this also applies to strong networks of institutions that may help dampen the interactions within the system.

3.3. What Distinguishes Human From Environmental Systems

Dynamic models of human-water interactions such as Wonderland bear a lot of resemblance to models of natural systems although additional processes related to technology, socio-economics, and institutions are introduced. However, the inclusion of humans does bring in new or unique features. *Reis and Sprecher* [2009, p. 1620] noted: "... most systems theorists recognize that individuals are able to self-reflect, and such reflexivity distinguishes human systems from other systems." Reflexivity occurs through cultural lenses, thereby making it possible to reproduce or change culture as a property of both individuals and structure [*Baker et al*., 2015]. People think or reflect about things or processes, attach a value to them, and develop certain preferences. *Holling* [2001, p. 401] suggests that human systems exhibit at least three features that are unique: foresight, communication, and technology. All of these unique human behavior aspects, including the informal nature of values and norms, add to the complexity of human-social systems and to the difficulty of modeling their behavior.

An element that arises from the cognitive abilities of self-reflection is that human decisions do not necessarily follow any set of rules or are "rational." The perspective on this issue may differ between the disciplines. As *Simon* [1986, p. S209] noted, "Economics has almost uniformly treated human behavior as rational. Psychology and sociology, on the other hand, have always been concerned with both the irrational and the rational aspects of behavior." And in 1978 (the year he won his Nobel Prize for Economics), Simon (1978) wrote: "The rational man of economics is a maximizer, who will settle for nothing less than the best."

The issue of rational behavior (or otherwise) is important for conceptualizing the coevolution of humans and water. Natural systems do exhibit long-term evolutionary behavior that can be expressed in terms of common organizing principles. These include ecological or vegetation optimality [*Eagleson*, 1982; *Rodriguez-Iturbe et al*., 1999; *Schymanski et al*., 2009], minimum energy dissipation [*Rodriguez-Iturbe et al*., 1992; *Zehe et al*., 2010], maximum entropy production [*Kleidon and Schymanski*, 2008], and optimum root zone storage [e.g., *Gao et al*., 2014a]. Similarly, nature operates under the constraints of natural laws or boundary conditions (e.g., gravity as in "water flows downhill," and the concept of water balance), as indicated in Figure 6 (top). In contrast, humans may make decisions away from any optimality principles and they may violate their own laws (see Figure 6, bottom). For example, they may extract water from a well, even though it is illegal to do so; and they can choose to live with pollution for other than optimality reasons. This makes it very important to understand, and model, the influence of cultural factors and associated values and preferences, which are likely to be more predictive of behavior than assumptions about rationality, or utility maximization [*Caldas et al*., 2015].

Again quoting *Simon* [1986, p. S209] "Everyone agrees that people have reasons for what they do," so irrationality does not imply that a decision is without reason. Rather "rational behavior simply implies consistent maximization of a well-ordered function, such as a utility or profit function" [*Becker*, 1962, p. 1]. This is a pragmatic definition reminiscent of how Kolmogoroff, founder of modern probability theory, defined deterministic and random models: "The possibility of using, in the treatment of a real process, schemes of well determined or of only stochastically definite processes stands in no relation to the question whether the real process is itself determined or random" [*Kolmogoroff*, 1931, p. 417]. Clearly, whether human behavior is random (irrational) or deterministic is not a scientific question. Rather it is a pragmatic modeling choice that will (usefully) depend on whether we see clear patterns with the amount of information available. Coevolutionary models may therefore account for human behavior by a stochastic treatment.

Whatever the exact process is by which humans make decisions, they are always based on values and preferences [*Warren et al*., 2011]. While values are generally considered as fundamental ideas about right and wrong, good and bad, desirable and undesirable, in the case of water management, following *Wescoat* [2013] and *Sivapalan et al*. [2014], we define values as the overarching goals of individuals and whole societies with respect to water use, conservation, and sustainability. Preferences affect the more detailed decision process. Traditionally, water resources management has assumed values and preferences to be exogenous to the water resources system. Systems analysis has then obtained viable solutions that are optimum with respect to such preferences, e.g., maximum water yield, maximum yield reliability, and minimum total cost. These may be conflicting, so compromises are needed [*Loucks*, 1977]. Values usually do not change rapidly with time, so if time scales of years or a few decades are of interest, the assumption of fixed values imposed exogenously on the water resources system make sense. However, when a longer-term

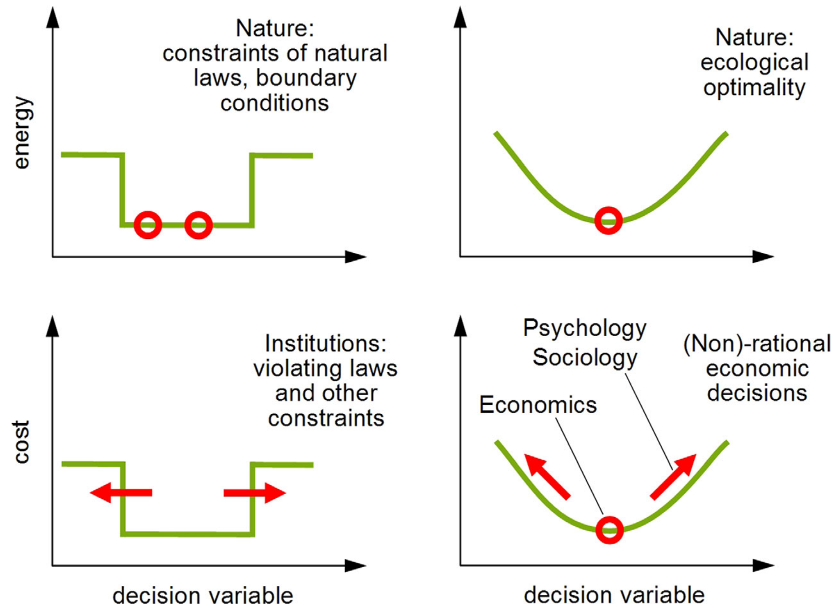

Figure 6. (top) Natural systems follow constraints and optimality laws. (bottom) Human systems may violate constraints and make irrational decisions. While in economics, humans are considered as optimizers, always following rational behavior, psychology and sociology allow for more complex, irrational behavior.

perspective is taken, it may no longer be appropriate to assume that they are fixed and specified externally, since they may change over time under the influence of education, advertising, changing cultural assumptions and the dynamics of the water resources system itself [*Norton et al.*, 1998]. Dynamic changes in the values and preferences through human-nature interactions and feedbacks should therefore be an important component in the representation of water resource systems [*Caldas et al.*, 2015].

3.4. Changing Values and Water Governance

When looking back at water resources management over the past century, it is clear that the values and preferences of society have dramatically changed. They changed from a preference for single purpose projects to multiobjective projects [*Russell and Baumann*, 2009], from an emphasis on structural measures to an emphasis on incorporating ecological values into water policy [*Gleick*, 2000], from short-term goals to longer time scale outlooks [*Loucks*, 2000], and from solely politics and expert-driven decision making to an increased role of community participation [*European Union*, 2000; *Carr et al.*, 2012].

An example of changing values is presented in Figure 7a from Western Australia [*Elshafei et al.*, 2014, 2015]. In the second half of the twentieth century, intensive agriculture was pursued in the Lake Toolibin catchment through conversion of native Eucalyptus forest to crops (e.g., wheat), which over decades led to rising water tables due to the reduced transpiration (fluctuating at daily time scales). The resulting land and stream salinization contributed to decreasing agricultural productivity of land, and loss of economic output. These processes led to a slowly increasing awareness of environmental issues from the 1970s and more intensified efforts at recovery.

Differences in the values may not only occur in time but also in space and these are particularly important in river basins where upstream and downstream water users are linked through the water flow in the river system. In fact, most water resources management problems have a very important spatial component, which requires trade-offs and compromise between conflicting interests in different parts of the river basin [*Loucks et al.*, 2005]. *Chen et al.* [2014] presented an example of spatial differences in values in the Kissimmee River Basin in Florida (Figure 7b). In the rural part of the catchment, severe flooding in the 1950s triggered remedial action in the 1960s in the form of river training which, however, degraded the local wetlands in the decades after. While locally this may not have been considered an issue, the community in the urban part of the catchment valued the environment more than flood mitigation (in the parts of the catchment that did not concern them directly). The urban group turned out to be more influential in the

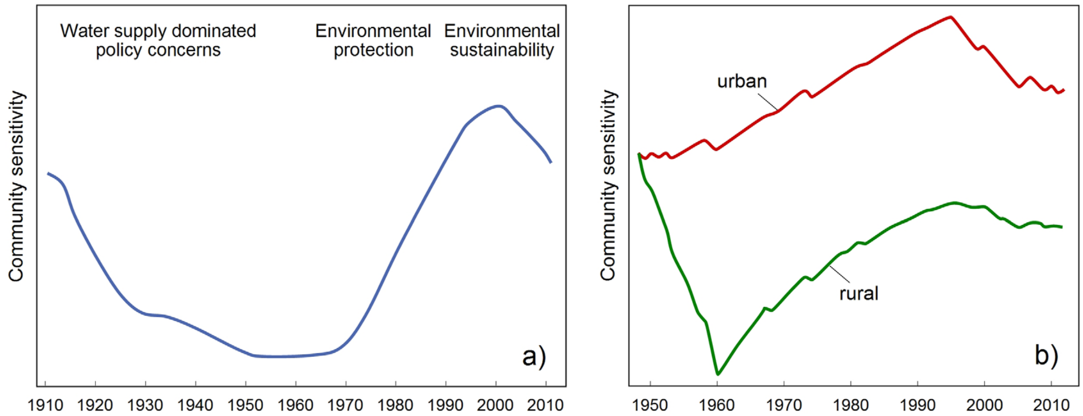

Figure 7. Evolution of simulated community sensitivity to environmental health (a) in the Lake Toolibin catchment, Western Australia [*Elshafei et al*., 2015], and (b) in the Kissimmee River basin, Florida, for rural and urban parts of the catchment (X. Chen and D. Wang, personal communication, 2015). Community sensitivity is an indicator of the value attributed by the community to environmental health.

overall river basin management, and the wetlands are currently being restored even though this tends to go against the interests of the rural, downstream communities.

Norton et al. [1998] examined how and why preferences evolve and change over time, based on findings from psychology and economics (research on revealed preferences, constructed preferences, and decision making under uncertainty), social psychology and sociology (social traps), and anthropology (coevolutionary adaptation of cultures and ecosystems). They suggested that preferences are formed in humans "by selection acting on traits that are transmitted both genetically and culturally, in a coevolutionary way. . . . Over time, preferences may be affected by human genetic evolution, education, technological change, the evolution of social systems, and the changing availability of environmental and other natural resources." [*Norton et al*., 1998, p. 201]. They noted that in modeling the dynamics of complex systems, it is impossible to ignore the discontinuities and surprises that often characterize these systems and the fact that they operate far from equilibrium in a state of constant adaptation to changing conditions. They therefore proposed a coevolutionary explanation for preference formation and suggested that it is different from the traditional optimization paradigm of economics in four respects: "(1) evolution is path dependent, meaning that the detailed history and dynamics of the system are important; (2) evolution can achieve multiple equilibria; (3) there is no guarantee that optimal efficiency or any other optimal performance will be achieved, due in part to path dependence and sensitivity to perturbations; and (4) 'lock-in' (survival of the first rather than survival of the fittest) is possible under conditions of increasing returns" [*Norton et al*., 1998, p. 202]. Lock-in here refers to the phenomenon that once established, the inertia of changing is so high that the preference will not change even though it is no longer desirable. An example of a lock-in phenomenon in water resource systems are the laws relating to water ownership in the western United States. When established the water laws stipulated that land ownership included ownership of the water underneath. The laws were easy to introduce but now that they are set in place, it is essentially impossible to take them back, even though this would be desirable from a regional water management perspective [*Culp et al*., 2014]. Another example are subsidies on the price of water and energy in several countries which were good when they were introduced; since then they have contributed to overexploitation of water resources, but cannot be reversed without a huge political cost [*Srivastava et al*., 2014].

Differences in the values also occur between scales from individuals to households, communities, and entire countries, and there are also interactions between these scales [*Gunderson et al*., 1995; *Holling*, 2001]. For example, cultural values drive the drafting of constitutions, which drive water laws, which drive water policies and contracts of the water industry at small scales, and so on (Figure 8b). Conversely, reflecting on the growth and organization of human societies, one can say that the larger entities in Figure 8b are themselves the result of the long-term coevolution of processes interacting at progressively smaller scales. Indeed, *Caldas et al*. [2015] suggested that cultural values can be considered as every day, lived practice which scales up in a "bottom-up" way. Note the similarities with how energy cascades through the Earth System where solar energy drives the global circulations which drive consecutively smaller-scale motions of the

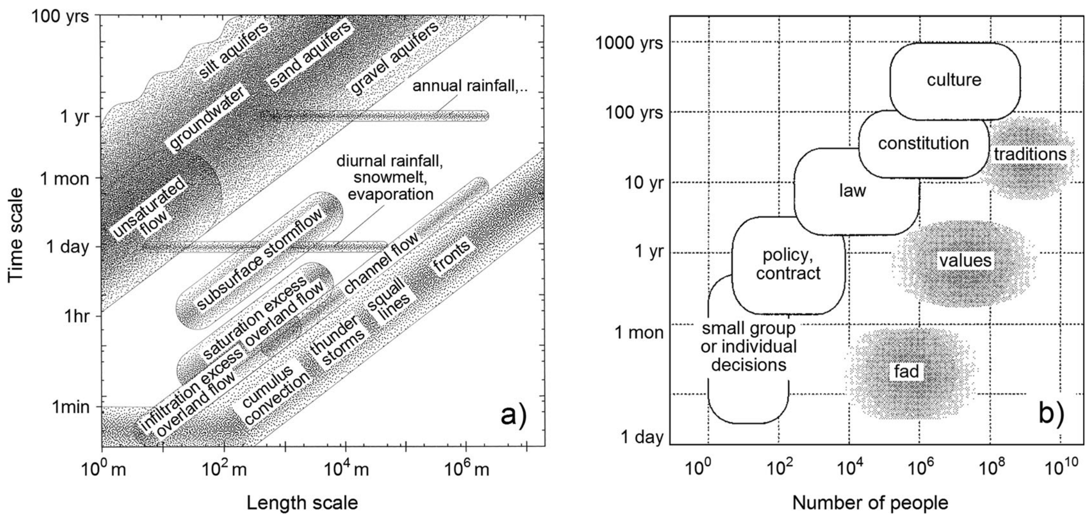

Figure 8. (a) Characteristic scales of hydrological processes [from *Blöschl and Sivapalan*, 1995]. (b) Characteristic scales of institutional processes [from *Gunderson et al*., 1995]. From *Panarchy* edited by Lance H. Gunderson and C.S. Holling. Copyright © 2002 Island Press. Reproduced by permission of Island Press, Washington, DC.

atmosphere and the ocean (for more insights, see *Blöschl et al*. [2014a]). Likewise, in the hydrological system, energy and mass cascade down to smaller scales (Figure 8a), but the large-scale processes arise through aggregation of processes at small scales, e.g., as when flow accumulates downstream in a river system.

Cumming et al. [2006] noted that many of the problems in managing natural resources arise because of a mismatch between the scale of management and the scales of the processes being managed. For example, values enshrined in the legal system may vary only slowly (e.g., water law in the western United States), while environmental change may occur faster. The unintended consequences of the management may become evident at much longer time scales (after generations), as is the case with river training effects on ecological degradation and increased flooding. In the Ogallala High Plains Aquifer in the U.S., groundwater depletion has persisted for at least 40 years in spite of a variety of policies and institutions in place to address the issue. *Sanderson and Frey* [2015] explain this conundrum as an outcome of a mismatch between the local scale of resource management and the regional scale of groundwater movement.

In a classic paper on hydrological scales that appeared in the twentieth anniversary issue of *Water Resources Research, Dooge* [1986, p. 49S] argued that "Most problems arising in catchment hydrology fall in the category of complex systems with some degree of organization." On the basis of the above arguments, it is clear that Dooge's statement applies equally to human-water systems due to the complex interactions across a hierarchy of time and space scales, in this case additionally driven by societal preferences and values.

In hydrology, we know that how exactly the hydrological response of a catchment changes with scale has a lot to do with the level of organization of that catchment. Random (disorganized) subsurface properties result in very different aggregation behavior of flow and transport than subsurface properties that allow for preferential flow [*Blöschl and Sivapalan*, 1995; *Western et al*., 1998, 1999]. The more organized the system is, the more quickly will a perturbation (such as a contaminant) spread through the catchment system. Analogously, in social systems, *Gladwell* [2006] pointed out that a few individuals can have a huge impact on the aggregate behavior of social networks, which can make ideas, products, messages, and behaviors spread more quickly through the system: this is akin to a social "preferential flow." Of course, the recent introduction of sophisticated forms of social media will likely have a significant impact on communication and thus on social "preferential flow."

Organization may be imposed from the top, as is the case in many governance systems, or it may emerge from the interaction of small-scale entities such as individuals and small communities. In the context of socio-ecological systems, *Ostrom* [1990] emphasized that self-organization of individuals who are in an interdependent situation is indeed a common phenomenon that leads to emergent system behavior. She noted that "... accepted theory has assumed that resource users will never self-organize to maintain their resources and that governments must impose solutions. Research in multiple disciplines, however, has found that some government policies accelerate resource destruction, whereas some resource users have invested their time and energy to achieve sustainability" [*Ostrom*, 2009, p. 419]. This finding has important implications for water governance as it shifts the emphasis toward empowering individual water users to assume more responsibility [*Bakker*, 2012].

3.5. Examples of Emergent Phenomena in Coevolving Human-Water Systems

The evolution of societal preferences and values seems to be a key factor in modern water resources management. The numerous river and wetland restoration projects around the world reverse, at great cost, river training and drainage projects that have been performed at similar cost, often less than a century before. In both instances, the projects were a reflection of the societal values and needs at the time of the projects, and the change in values precipitated a different water resources management action. In effect, water resources management solved one problem but created another problem that was not foreseeable at that time. Following *Odum* [1982], this situation has been referred to as a "tyranny of small problems" [*Sivapalan*, 2015]. They reinforce the view that sustainable water resources management should take these long-term changes into account and, ideally, anticipate future changes. In a similar vein, there are often spatial differences in the values and interests that give rise to conflict and a need for water resources management action.

The examples presented in Table 1 illustrate the rich diversity of emergent phenomena arising from human-water feedbacks. The table also indicates the time scales involved. In most instances, there are interactions of fast and slow processes driving the system dynamics.

Some of these phenomena are already being explored within the field of socio-hydrology [*Sivapalan et al*., 2012, 2014; Troy et al., 2015a]. The levee effect relates to the observation that periods of less frequent flooding (e.g., due to flood protection structures) are often associated with increasing vulnerability. Socio-hydrological models [*Di Baldassarre et al*., 2015] could help explain this effect. A lack of flooding leads to a loss of community memory about flooding and the community, unaware of the risks moves into flood-prone areas. When an exceptionally high flood occurs, the levees are overtopped and the damage is much larger due to the assets that have accumulated in the flood-prone area during a period of infrequent flooding. Another phenomenon may manifest in agricultural societies, where a range of practices or technologies are successfully adopted to increase irrigation efficiency and save water for the environment, only for the saved water to be used by downstream users or contribute to the expansion of the irrigation area, and thus no net savings of water [*Zhang et al*., 2014]. This irrigation efficiency paradox has been attributed to the absence of norms governing how water saved should be re-allocated [*Scott*, 2011].

Many agricultural regions of the world are experiencing decrease of human water use through reallocation away from irrigated agriculture toward the environment. This is a human adaptation that is driven by increased environmental consciousness and the diminution of agriculture as a fraction of the economy, as documented by *Kandasamy et al*. [2014] in the Murrumbidgee River Basin in eastern Australia. The observed "pendulum swing" in the competition for water between human use and the environment (also called the peak water paradox [*Sivapalan et al*., 2014] has been reproduced in a socio-hydrologic model that allows for the dynamic change of environmental consciousness [*van Emmerik et al*., 2014].

These and other examples of emergent socio-hydrologic phenomena highlighted in Table 1, as arising from coevolution of coupled human-water systems, give rise to three different lines of enquiry in socio-hydrology: historical, comparative, and process socio-hydrology.

a. Historical socio-hydrology: human-water interactions have shaped society over the entire human history. Ancient civilizations such as the Mayas, the Hohokam, Angkor Wat, and the Harappa thrived and eventually dispersed, and water scarcity was among the reasons attributed for their collapse [*Pande and Ertsen*, 2014; *Dunning et al*., 2012; *Penny*, 2014]. Much can be learned by a systematic historical study of the coevolution and the mechanisms that may have led to these dynamics, and contrasting these with modern civilizations in which more developed institutional structures are present. The advantages of

Table 1. Emergent Phenomena Arising From Human-Water Feedbacks Due to Interaction of Slow and Fast Time Scales and Change of Values in Space and Time

Change of Values or Preferences in Time	Difference of Values or Preferences in Space: No Difference of Values or Preferences in Space	Difference of Values or Preferences in Space: Difference of Values or Preferences in Space/Place
No change in values or preferences in time	Collapse of system (e.g., dry out of Aral Sea due to short-term irrigation and long-term water balance and economy) [*Cai et al*., 2002] Resource capture by the elite (e.g., building of Narmada Dam, India, and loss of livelihood of locals due to short-term business interests and long-term resource depletion) Lock-in of groundwater depletion (e.g., groundwater overexploitation in India due to subsidized energy, interaction of short-term pumping at no cost, and long-term water balance) Increase in vulnerability due to overreliance on technology (e.g., collapse of the Mayas due to drought and dependence on reservoirs [*Lucero*, 2002])	Upstream-downstream conflicts (e.g., Mekong hydropower development affecting livelihood of downstream rural/fishery communities due to short-term flow disruption and long-term environmental degradation and economic development) Large-scale water transfers (e.g., South-North project, China, associated with short-term flow disruption and long-term food security) Operation of hydropower reservoir for flood mitigation (e.g., Orlik reservoir upstream of Prague, short-term loss of electric power, and long-term flood risk reduction)
Change in values or preferences in time	River training and restoration (e.g., Sacramento river management due to short-term flooding and long-term change in environment) Levee effect (e.g., settlement pattern in the Netherlands due to short-term flood protection and long-term flood plain encroachment) Efficiency paradox (e.g., increase in water consumption in the Tarim basin, China, in spite of increased water use efficiency as a result of increase of agricultural land, short-term irrigation, and economic gains and long-term policy changes)	Adaptation: peak water paradox (e.g., increasing upstream water extraction and downstream degradation in the Murrumbidgee basin, Australia, short-term economic decisions, and long-term environmental damage) Virtual water trade (e.g., food trade from South America to Asia, short-term economics, and long-term food security) Coastal hypoxia (e.g., hypoxic zone in Gulf of Mexico resulting from agriculture in Mississippi basin, short-term profits, and long-term receiving water quality degradation)

studying ancient civilizations are that their history covered a long time period, they were relatively isolated, and their fate was governed by simpler mechanisms than prevail today.

b. Comparative socio-hydrology: the coupled human-water systems that are present today anywhere in the world are also the legacies of coevolution. Much can be learned by comparing and contrasting today's water phenomena at different places and seeking common explanations. This can be done by organizing them into groups of similar behavior [*Srinivasan et al*., 2012] and by studying them across hydrological and socio-economic gradients, in the spirit of the *Prediction in Ungauged Basins* initiative [*Blöschl et al*., 2013a]. The study of socio-hydrological behavior across gradients can be assisted by trading space for time, and accounting for the coevolution index (equation (6)) that measures how far the system is away from equilibrium.

c. Process socio-hydrology: the examples of socio-hydrological phenomena in Table 1 indicate that the change of community values either in time or space lies at the heart of several of these phenomena. They come about by the aggregation and interactions of the behavior of individual agents and groups of agents. Much can also be learned by studying this aggregation behavior in considerable process detail through field studies, surveys, and the use of agent-based models [e.g., *Evans and Kelley* 2004; *Gober et al*., 2014]. This is where the interactions with economists, sociologists, and psychologists are particularly important [e.g., *Wutich et al*., 2014].

4. Framing and Modeling Real-World Problems

In the previous section, we have presented narratives of several socio-hydrologic phenomena, which are expressed in the form of emergent dynamics, patterns, and paradoxes that result from long-term coevolution of coupled human-nature (water) systems. The phenomena may be generic (any of the broad class of paradoxes that manifest in several places, e.g., the levee effect, irrigation efficiency paradox), or they could be place based, reflecting the unique characteristics of a place and its water history.

Why do these phenomena occur and what is exactly the nature of human-water interactions? In order to generate and test hypotheses about the mechanisms causing these phenomena, it is useful to frame and model the phenomena in a quantitative way [*Troy et al*., 2015b; *Di Baldassarre*, 2015]. Often there may exist more than one plausible explanation for the occurrence of a phenomenon [*Chamberlin*, 1965]. For example, in the case of the collapse of the Easter Island civilization, resource overexploitation, climate change and diseases introduced from outside can be competing hypotheses or multiple stressors [*Brandt and Merico*, 2015]. Testing quantitative models may then help in deciding which of the hypothesis is more realistic, given the available evidence.

The framing and modeling may be performed at different levels of detail, depending on the purpose. The models can be highly comprehensive and include a lot of detail about a particular place. Alternatively, they can be stylized models that abstract the system with much less detail but with a view to capturing holistic aspects of the entire system in a general way. There can be a whole range of models in between with respect to their level of detail.

4.1. Possible Steps of Framing and Modeling Human-Water Interactions

Table 2 presents possible steps for framing and modeling human-water interactions and contrasts them to those of other model genres. The steps involved in developing socio-hydrological models are similar to those of coupled dynamic environmental models, but there are additional aspects that need to be taken into account. These additional aspects are shown in the right column of the table. Likewise, the steps involved in developing coupled dynamic environmental models are similar to those of typical hydrological models, but there are additional aspects (middle column). Finally, the left column shows the framing and modeling steps of typical hydrological models. Of course, the steps follow the normal scientific method of modeling adopted in the natural and social sciences [e.g., *McDonald*, 1989; *Jakeman et al*., 2006], but there are specifics of socio-hydrological models that are worth discussing here. Development of socio-hydrological models can also benefit from the advances made in the wider discipline of socio-ecological modeling [*Schlüter et al*., 2012].

Step 1 Phenomenon, domain, scale

This step involves developing a general statement of the phenomenon and setting boundaries for the problem, both in space and in terms of governing variables. As compared to phenomena represented by other environmental model types, socio-hydrological phenomena tend to be more complex. Emergent phenomena due to time scale interactions may include tipping points, regime shifts, and system lock-ins. The phenomena are often obtained from narratives presented by stakeholders and experts from different disciplines. These narratives should capture the diversity of values and preferences held in the community. An important consideration in socio-hydrological models is what processes to internalize (i.e., represent within the model) and what processes to leave as external forcing and to be prescribed as boundary conditions. Ideally, the external forcing should not be affected by the system behavior and it should be known.

Step 2 The perceptual model

This step involves developing a perceptual model that describes the system, i.e., (one or more) working hypotheses about the underlying causes of the phenomenon. Since feedbacks between processes and scales are particularly important, it is often useful to start the perceptual model with drawing causal loops that represent the feedbacks of the system. The drawing of the causal loops may be based on a narrative of the problem (as is typically done for stylized models) or it could be based on preliminary data analyses (as is often the case in comprehensive models). It is usual to associate process time scales with the feedbacks, e.g., they may either operate at event, seasonal or centennial time scales [e.g., *Gaál et al*., 2012]. Causal loops are particularly effective if experts from different fields are involved since the causal loops foster group model building [*Vennix*, 1999]. Figure 9a presents an example of a causal loop diagram for the levee effect [*Di Baldassarre et al*., 2015], based on a narrative that represents feedbacks between people and floods in an urban environment, including the construction of levees. At this stage in the framing, the focus is on identifying the essential system components and their interactions conceptually. The actual state variables are defined later in Step 3. The arrows in Figure 9a represent relevant feedbacks (+ and – in Figure 9a

Table 2. Seven Steps of Framing and Modeling Hydrological Versus Coupled Dynamic Environmental Versus Sociohydrological Processes

	Hydrological Models (Simple Systems)	Coupled Dynamic Environmental Models (Complex Systems)—Framing in Addition to Hydrological Models	Sociohydrological Models (Complex Systems With Humans)—Framing in Addition to Coupled Environmental Models
Step 1: Phenomenon, domain, scale	Specify phenomenon (e.g., rainfall-runoff transformation, scaling of floods) Specify control volume (e.g., catchment) Specify study period (e.g., events) Specify purpose of modeling (e.g., flood estimation)	Choose control volume by considering what process to internalize and what process to leave as external forcing (external forcing should not be affected by system behavior) Study period typically longer (e.g., centuries) Phenomena typically more complex (e.g., vegetation patterns)	Phenomena typically even more complex (e.g., macroscale phenomena such as levee effect, irrigation paradox). These phenomena are often defined through narratives
Step 2: Perceptual model	Bottom up (mechanistic) from laboratory experiments (e.g., Darcy) Or top down from response data (e.g., UH) Based on hydrological data and prior knowledge (e.g., existing modeling concepts)	Usually bottom up due to complexity of processes (top down approach of inferences from response data tends to break down) Guided by observed patterns of environmental data and prior knowledge Causal loop diagram to conceptualize process interactions, including interactions between time scales	Causal loop diagram assisted by narratives of phenomena to visualize alternative hypotheses Decision on whether phenomena are represented explicitly or to emerge from system dynamics Allow for change in values, if appropriate Possibly allow for role of "social preferential flow" and randomness in human decisions
Step 3: Choice of state variables	Conventional choices (e.g., water stores, groundwater, unsaturated zone, lakes, snow)	Small number of variables usually of advantage, so variables of minor influence may be omitted and variables with similar effects may be combined Variables should be measurable Classify into fast and slow variables	Choice of variables more difficult due to four subsystems: natural (e.g., pollution), infrastructure/technology (e.g., reservoirs), socioeconomics (e.g., wealth, population, values), institutions/governance (e.g., land use planning) Values are a key state variable for a long-term treatment Mediating variables that drive others are useful, if they have independent dynamics
Step 4: Causal factors that affect state variables	Causal factors can be state variables or external forcinge.g., soil moisture change = f(water potential; precipitation, radiation) Preliminary data analysis and learning from other places may also assist	Larger choice of factorse.g., landform change = f(soil moisture, runoff, vegetation; tectonic uplift, precipitation) Causal loop diagrams and known balance equations (e.g., sediment balance) may assist in choice of factors (and therefore coupling)	Still larger choice of factorse.g., change in infrastructure = f(flood damage, wealth; global economy) Causal loop diagrams and known balance equations (e.g., financial budget) may assist in choice of factors (and therefore coupling)
Step 5: Functional relationships for Step 4	Based on universal laboratory (e.g., Darcy) or field data-based (e.g., Chezy) relationships Possibly requires upscaling Balance equations imply additive relationships Dimensionality arguments (e.g., resistance proportional to velocity in laminar flow but velocity squared in turbulent flow)	Wider range of possible equations (e.g., Exner equation) Use of local data may require upscaling Dimensional analysis gives guidance on combining parameters (Buckingham Pi theorem) Scaling analysis to help identify fast and slow state variables (if equations are known), possibly revise state variables (Step 3)	Additional guidance by socioeconomic data (e.g., surveys, censoring) and narratives Translate narratives into cause-effect, i.e., functional relationship Use of local data (particularly in comprehensive models) Additional guidance by the implications for system dynamics (e.g., concave versus convex utility functions; bistability of system, . . .)
Step 6: Parameter estimation	Usually parameters inferred from response data (e.g., parameter calibration on hydrographs) Uncertainty analysis of parameters, possible parameter ranges, and their impact on model predictions	Measurement of parameters more common as calibration often difficult Laboratory and field experiments Learning from other environments Proxy data (e.g., soil depth inferred from vegetation height)	Disassemble model into components and estimate parameters separately for different streams of data (e.g., surveys, censoring, financial data, demographic) in addition to environmental data Possibly calibration to multiple, observed time series Reassemble model and estimate feedback parameters against emergent phenomena Evaluate effect of model parameters on path dependence and lock-ins of model dynamics
Step 7: Model validation and uncertainty	Testing model against independent records of response data (e.g., hydrograph from a period not used for parameter estimation) Testing model against other state variables (e.g., soil moisture, snow, groundwater) Identify sources of possible mismatch If model validation not satisfactory (relative to the goals), go back to Step 1 and reframe problem	Test model against spatial patterns of state variables (e.g., vegetation patterns, meander patterns) Chronosequences to assist in testing long (coevolutionary) time series Explore solution space including the interaction of slow and fast variables, critical transitions, and equilibria to assist in process understanding, possible model revision, and extrapolation to other places	Test component models against different streams of data If phenomena are repeatable in space or time, test model against similar situations at different places or in different time periods If phenomena are not repeatable, no full validation is possible (because information on phenomena has been used for parameter estimation) Sources of uncertainty may include nonoptimum behavior of humans

denote positive and negative feedbacks), remain conceptual at this stage, and associated functional relationships are defined later in Step 5.

Step 3 Choice of state variables

The state variables are the backbone of the model, so their choice is an extremely important framing step. What is considered variable (and must therefore be included as a variable) or fixed, depends on the nature of the model and the phenomenon. Clearly, this choice is an art, although one strategy that can be adopted is to start simple and add more variables only as required to reproduce the phenomenon of interest. Classifying variables as fast and slow (on the basis of the rates of change) may help in the framing process. Two state variables may share the name but represent processes at different time scales. For example, two separate state variables may represent precipitation at monthly and centennial time scales and they may exhibit completely different dynamics. To be practically useful, all the variables included in the model should be measurable, either directly or through the use of appropriate surrogate or proxy information. Due to its paramount role in socio-hydrological processes, human values or preferences are prime candidates for state variables. *Elshafei et al*. [2014] suggest that environmental community sensitivity (as shown in Figure 7) can be brought into a socio-hydrological model to represent the human values as a state variable. *Di Baldassarre et al*. [2013a, 2013b] define a risk awareness variable, M, that encapsulates the collective preference of the community in relation to flood risk aversion. The greater M, the greater will be their preference to avoid settling in flood-prone areas. Further suggestions for the range of possible state variables in socio-ecological systems are given by *Ostrom* [2009].

Step 4 Causal factors that affect state variables

Causal factors affecting each state variable can be external (prescribed) factors (e.g., precipitation, GDP of a country, legal conditions), other state variables or the state variable itself. Due to the complexity of socio-hydrological models, it is suggested to first decide what causal factors to include in each equation (Step 4) before specifying the exact functional relationships (Step 5). The causal loop diagrams (Step 2) provide guidance on the choice of causal factors. For example, the factors that affect the environmental community sensitivity variable of *Elshafei et al*. [2014] include the economic well-being (income, unemployment, . . .), environmental status (water availability and quality, biodiversity), cultural dynamics, and exogenous factors such as the existence of an active green movement, relative levels of corruption, and the global economy. Factors that affect flood risk awareness may include the previous experience with damaging floods, economic well-being, and cultural factors (such as the value attached to living in a home with a view) [*Burningham et al*., 2008].

Step 5 Functional relationships by which causal factors affect state variables

The next step is the specification of functional relationships that describe each of the feedbacks between the state variables as well as the effects of the external forcings. The functional relationships can be conceptualized using intuition (as is often the case in conceptual models), through recourse to data analysis (if the appropriate data exist), taken from the literature on related studies, or can be based on consensus principles (e.g., logistic growth) [*Elshafei et al*., 2014]. The functional relationship between values and human behavioral response can be obtained through choice experiments [e.g., *Morrison et al*., 1999] that explore the judgment of a set of experts or stakeholders through questionnaires. A useful principle is to choose similar complexity for the various components of the model (e.g., economy, hydrology, technology). The functional relationships may operate at different time scales (see equations (1), (2), (4), and (8)) which are related to the time scales of the state variables they define. For clarity, it may be useful to specify the time scale ratio, ε, explicitly. The equations must be dimensionally consistent, which limits the possible combinations of the variables. Always, as in many other branches of environmental science, dimensional analysis may assist in keeping these functional forms compact and parsimonious, and non-dimensionalizing the relationships may reduce the number of parameters [*Viglione et al*., 2014]. If the underlying equations are known, scaling analysis may be a useful way to determine the magnitudes of individual terms in the equation, discard minor terms, and thus reduce model complexity [e.g., *Milik et al*., 1996]. Additionally, for the case of stylized models, some guidance may be given by the implications of the functional form for system dynamics (e.g., concave versus convex objective functions for the case of optimization (normative modeling).

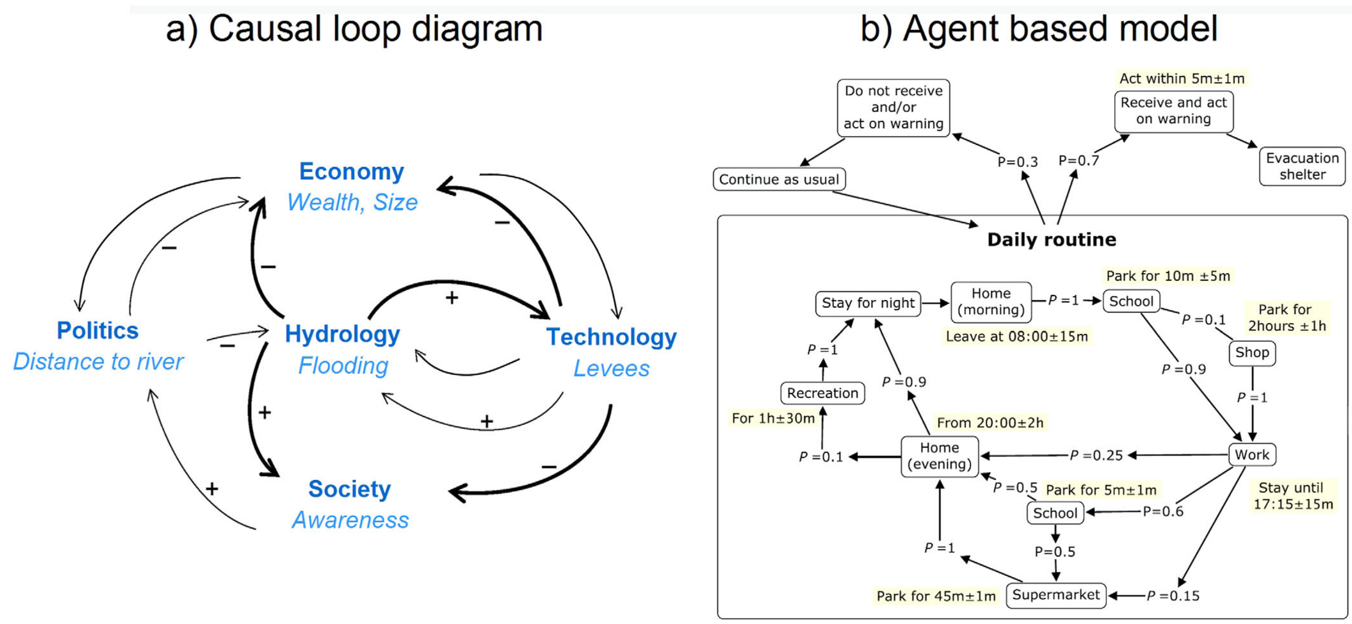

Figure 9. (a) Causal loop diagram showing how hydrological, economical, political, technological, and social processes are all interlinked and gradually (continuous thin arrows) coevolve, while being abruptly (continuous thick arrows) altered by the sudden occurrence of flooding events [*Di Baldassarre et al.*, 2013a, 2013b]. (b) An agent-based model of the daily routine generated from travel survey and census data for a female agent from a household of four and who is employed (see Step 5)—agent starts the day at 8 A.M. with standard deviation of 15 min, travel, via school to drop children off, to work, with a 0.1 probability of visiting the shops en route etc. This daily routine is interrupted when they become aware of a flood incident, e.g., they will choose to evacuate to the nearest shelter with a probability of 0.7 etc. [*Dawson et al.*, 2011].

In agent-based models, on the other hand, the functional relationships involve probabilities which serve the role of parameters. Figure 9b presents an example of an agent-based model, which was based on the results of a survey carried out for flood incident management to assess (i) how agents behave under normal conditions that determine where they are at the start of a flood event and (ii) how they respond to a flood event. Each agent is described in terms of their possible states, the actions they can take and the transitions between states. To capture the inherent variability and uncertainties in human preferences, the daily routines are described in probabilistic terms. In such an agent-based model, even if the behavior of individual agents is simple, collectively the model can exhibit complex, emergent patterns because of the interactions between individuals. Note the similarity between Figures 9a and 9b. Figure 9a represents the causal loop for a problem, whereas Figure 9b is the implementation of a causal loop on the basis of the choices of state variables, causal factors and functional relationships.

Step 6 Parameter estimation

Because of the many coupled processes involved, the difficulties with parameter estimation in socio-hydrological models multiply many-fold relative to hydrological models [*Brun et al.*, 2001]. There are also more streams of data such as population size/density, area under irrigation, reservoir storage, and agricultural productivity, in addition to the usual hydrological data. Following *Beck* [1999], we suggest addressing these difficulties by the classical procedure of disassembling the model into its parts and subsequently reassembling. This means for both stylized models and comprehensive models one would estimate the parameters separately for the individual component models or different time scales. The latter has the advantage that it may be possible to assume the slow process constant when estimating the parameters of the fast process, and that the fast process averages out when estimating the parameters of the slow process. The former has the advantage that different data groups can be efficiently exploited. For the hydrological model, one would estimate the parameters in the usual way, assuming all other components as external factors. Similarly, the parameters of the economic part would be estimated from economic data assuming the hydrology is prescribed, and the parameter associated with the dynamics of human values could be estimated using, for example, data from revealed and stated preference methods [e.g., *Adamowicz et al.*, 1994], or surveys of newspaper articles over a long period of time [*Elshafei et al.*, 2015]. Demographic data may be used to estimate the parameters associated with population dynamics [e.g., *Lutz and Samir*, 2010]. Once the parameters of the component models are estimated, the whole model is reassembled and the parameter estimation process is repeated, with an emphasis on the feedbacks, i.e., those parameters that link the model components. In the simple case of the badland model (equation (2)), these were parameters b and c, but in more complex models, there will be several parameter vectors that need to be estimated. Some of these parameters represent sensitivities, such as the environmental community sensitivity [*Elshafei et al*., 2014], which may be estimated on the basis of surveys, although senstivities may be highly variable and difficult to estimate in a representative way. Other parameters cannot be directly estimated and need to be calibrated by making use of the entire model. If these parameters manifest as clear signals in the observations, then these present a way to estimate them. Emergent phenomena can provide guidance on the selection of the feedback parameters, in particular for stylized models. Additionally, space-for-time substitution may assist in learning about the relative roles of fast and slow processes (as quantified by the coevolution index, ς) and how they manifest in the landscape. Diagnostic analysis of the complete model through splitting into fast and slow processes may provide insights into the relative importance of some of the parameters and help to prioritize the parameter estimation exercise, and this can be assisted by more traditional sensitivity analyses. Finally, and more pragmatically, some parameters may be transferred from other places that exhibit similar behavior [*Blöschl et al*., 2013a].

Step 7 Model validation and uncertainty

For the reasons outlined in the previous step, the idea of disassembling and later reassembling can be the basis also for a validation strategy. Individual components of the model can be validated by the usual split sample method where part of the data set is used for parameter estimation and the remainder of the data are used for validation. The splitting of the data can be into different time periods, different places, or different response variables. For the validation of the entire reassembled model, there are two possibilities. The first is when the socio-hydrological phenomenon of interest is repeatable in space or time. This means it could occur in different periods at the same place (e.g., drought-settlement interactions in Western China may be similar in different centuries with similar drivers [*Liu et al*., 2014; *Lu et al*., 2015]), or it could occur at different places in the same period (e.g., the pendulum swing of environmental values in the Murrumbidgee was also felt in Lake Toolibin in Western Australia [*Elshafei et al*., 2014]). In this case, the phenomena at different time periods or places could be used for model validation. The second possibility is when the socio-hydrological phenomenon of interest is not repeatable, i.e., it has unique features that are very unlikely to be repeated [*Phillips*, 2007; *Vergne and Durand*, 2010]. In such a situation, it will not be possible to validate the model in the normal sense. This means that the model will likely have little predictive power beyond the case study of interest. However, the model can still be very useful to explain the local socio-hydrological phenomenon and to explore the system dynamics, including time scale interactions. Such a model can also be very useful to further the general understanding of socio-hydrological processes, as pointed out by *Oreskes et al*. [1994]. In all instances, it is important to explore the solution space to understand the interaction of slow and fast variables, in particular the role of changing values in time and space, and the associated model uncertainties.

While Table 2 presents the seven steps in a sequential fashion, the framing and modeling is of course an iterative process that may not only involve a loop from Step 7 back to Step 1 (in case the validation is not satisfactory) but also sub-loops between individual steps as required.

4.2. Model Type and Model Complexity

It is useful to highlight the specific characteristics of the different model types with regard to their applicability, strengths, and weaknesses, and their treatment in the framing and modeling process.

4.2.1. Comprehensive System of System Models

The comprehensive (or system-of-system) models, typically, represent the sub-systems by individual modeling components, including the natural resources system, the infrastructure system associated with technology, the socio-economic system, and the institutional system of administration, legislation, and regulation of water (see section 3). Depending on the problem, these subsystems will vary and could be divided into more parts. Each component model is based on well-established principles and methodologies from the relevant disciplines. In many instances, these models are spatially explicit, particularly if they address spatially explicit management questions. Examples include land management and its impact on water quality [*Van*

Delden et al., 2007], flood risk assessment in a regional context [*Brouwer and Van Ek*, 2004], hydropower development and sediment management [*Wild and Loucks*, 2014], groundwater extraction and drought mitigation [*Cai et al*., 2015], and water-food-energy-environment nexus [*Yaeger et al*., 2014]. In each of these cases, one is interested in the spatial pattern of the socio-hydrological processes and in particular the spatial connectivity and the interactions between social and hydrological processes locally and at large spatial/administrative scales.

The comprehensive models have the advantage that, because of their process detail, they can be readily applied to real-world management problems in specific places. However, this comes at the cost of the effort needed to build the models. It may be very difficult to specify all the required parameters in a realistic way. Also, because of the complexity, it is very challenging to understand the overall system behavior for different parameter combinations and to reveal long-term, large-scale phenomena.

The steps of framing and modeling adopted here have a number of specific features. Since the overall model is usually compiled by linking several existing component models together, the perceptual model relies on the structure of each component and its appropriateness for the problem at hand. Similarly, the state variables are already chosen with the choice of the component models. The causal factors and functional relationships embody the linkages between the component models and therefore the feedbacks. The same process is not usually represented by two or more state variables at different time scales (e.g., equations (1a) and (1b)) but there is potential to do so. Normally, parameters are estimated from local data and through calibration of the component models off-line. Similarly, the component models are tested individually on local data, but one would also test whether the entire model captures the overall socio-hydrologic phenomena of interest (Table 1).

4.2.2. Stylized Models

The stylized models, typically, represent each subsystem by a single differential equation. They often involve explicit representations of slow and fast processes. The slow processes usually involve accumulation and depletion of various stocks (natural resources including water, wealth, human values, technology, demography, etc.). The stylized models tend to be lumped (i.e., have no spatial dimension). Examples include human-flood interactions in an urban setting [*Viglione et al*., 2014; *O'Connell and O'Donnell*, 2014], the competition for water between agriculture and the environment [*van Emmerik et al*., 2014; *Liu et al*., 2015], groundwater depletion in large aquifers [*Tidwell et al*., 2004], and more generally, the feedbacks between economic productivity and environmental degradation [*Milik et al*., 1996] (Figure 5). In each of these cases, one is interested in the overall system behavior, in particular the mechanisms that contribute to any emergent phenomena. The main purpose of these models is to perform exploratory analyses to understand the system dynamics in typical socio-hydrological situations.

The stylized models have the advantage of transparency and ease of use. It is possible to fully explore their dynamic behavior space for all parameter combinations, including any emergent behavior and the borders between stability and instability, as illustrated in the Wonderland example (Figure 5). This can provide guidance for decision making but at a strategic level. Their disadvantage is the difficulty of estimating realistic parameters since they represent aggregate behavior that cannot directly be translated into local-scale decisions.

The steps of framing and modeling allow more flexibility than in the case of comprehensive models. There are benefits to having a small number of state variables, as this limits the dimensionality of the problem. There is often an inverse relationship between the number of variables or components included and the generality of the model. The variables that should be included are only those that exhibit independent dynamics. It is not unusual to represent the interplay of time scales by explicitly defining fast and slow variables (equation (1)). Causal factors and functional relationships may often be obtained from a general understanding of the holistic system. Since the focus is on phenomena (rather than time series), the parameter choice can be based on different places where the phenomenon may have manifested. Validation mainly consists of the test of whether the overall socio-hydrologic phenomena of interest (Table 1) can be reproduced for the right reasons.

4.2.3. Iteration Between Comprehensive and Stylized Models

Depending on the problem, the model that is developed can fall anywhere in between the two end-members outlined above. Because of their different strengths and weaknesses, the model types are complementary. A useful strategy may involve usage of both model types in an iterative way [*Hipsey et al*., 2015]. Figure 10 illustrates this idea. One would start with a stylized model. Once the system behavior and the role of individual processes are better understood, one embarks on building a comprehensive model that includes specific local features. The stylized model will provide guidance on how to frame the comprehensive model, the relevant feedbacks, and the level of detail needed. Once the comprehensive model has been compiled, there is also value in abstracting this model into a stylized model to explore the system characteristics in a more systematic way. Also, the stylized models may provide a benchmark test for the more detailed comprehensive models. The iteration between comprehensive and stylized models may assist in reducing the model complexity of the comprehensive model by reducing the number of state variables through established procedures such as Model Order Reduction [*Schilders et al*., 2008; *Bruna et al*., 2014], or increasing the complexity of the stylized model to account for important local features.

An example of exploiting the synergies of stylized and comprehensive models is the work of Srinivasan who developed socio-hydrological models to reconstruct past system behavior and to diagnose the causes of a major water crisis in the city of Chennai in India [*Srinivasan et al*., 2010; *Srinivasan*, 2015]. The comprehensive model included such components as water flowing into the reservoir system; diversion and distribution by the public water utility; groundwater flow in the aquifer beneath the city (using MODFLOW); supply, demand, and prices in the informal tanker-truck-based water market; and consumer behavior. The stylized model included both fast processes such as short-term reservoir management and source switching by consumers; as well as slow processes such as long-term investments in infrastructure by the water utility (pipes and reservoirs) as well as users (wells, piped connections), but all in a lumped way. In this case, the experience with developing the comprehensive model helped with the development of the stylized model, which was used to fully explore the state space for different water management situations. The stylized model of *Srinivasan* [2015] has the advantage that it can be exported more easily to other cities with similar water issues.

5. So How Does Socio-hydrology Help With Water Management?

So far, we have discussed the development of socio-hydrologic models involving time scale interactions and the coevolution of coupled human-nature systems, with explicit inclusion of changing human values. These can be place-based comprehensive models based on individual case studies or generic stylized models focused on specific phenomena. How could they help with water resource management?

Generally, managers are interested to know: (i) the future consequences of current decisions and (ii) the mix of current decisions they should make to achieve a desired future outcome. For strategic decisions that concern long-term investments, large-scale changes to human settlement patterns, and major policy changes, the focus is on the long-term (decadal to centuries) and large spatial scales (regional to national). Examples are long-term strategies to manage groundwater depletion of large aquifers [*Scanlon et al*., 2012; *Gorelick and Zheng*, 2015] and national-scale flood risk management [*Merz et al*., 2010; *Hall et al*., 2014].

If the long-term evolution in human preferences or values is included in the models in a dynamic way (in addition to the dynamics of the environment, technology, demography, economy, and governance), then they are amenable to decision making over long time scales.

Socio-hydrological models can assist with management in three ways: (a) to facilitate stakeholder participation, (b) to help decision makers through the generation and assessment of alternative futures, and (c) to learn from the experiences of other similar places, and move toward generalizations beyond individual case studies.

5.1. Facilitating Stakeholder Participation

Guidelines for water management such as the European Water Framework Directive and the U.S. Clean Water Act now require public and stakeholder participation, as it enhances water resource management and involves individuals and groups in a democratic way [*Carr et al*., 2012]. Participation is particularly important but also challenging in managing large-scale and complex water systems such as the Great Lakes [*Carr et al*., 2013; *Krantzberg et al*., 2015]. Participation can assist management in several ways. It ensures acceptance, ownership and buy-in to the decision process. It also facilitates the social learning processes that typically involve a variety of different types of knowledge, and increases the likelihood that contentious trade-offs will be investigated and resolved through the decision-making

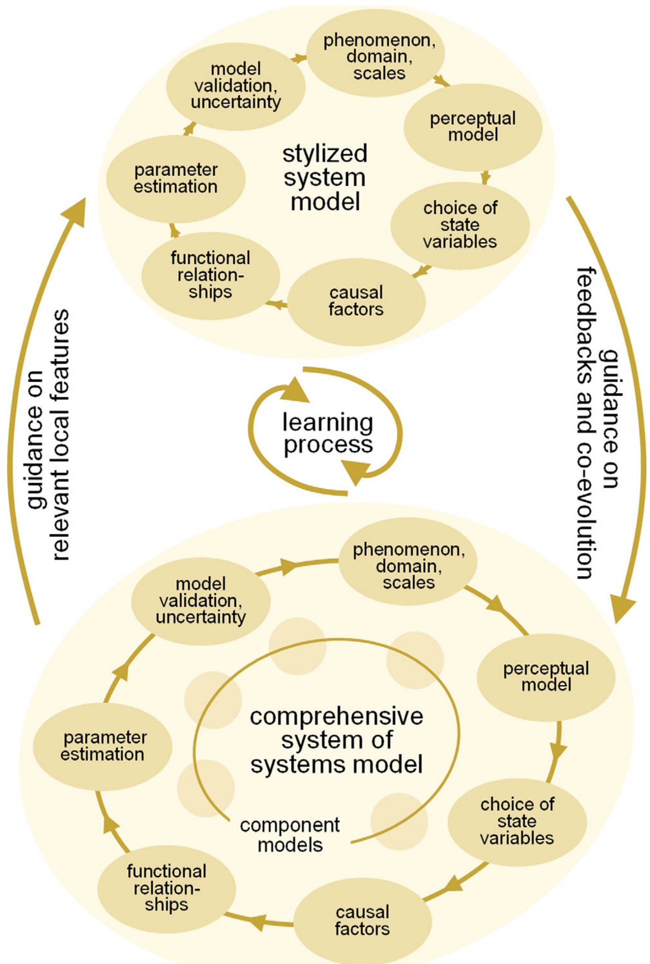

Figure 10. Strategy of socio-hydrological model development and enhancement through iteration between stylized models and comprehensive system of systems models. For each model type, seven steps of framing and modeling are shown.

process. Socio-hydrologic models, being coupled human-water system models with explicit inclusion of changing values, are therefore ideal tools to facilitate the participation of stakeholders in the management process.

One of the effective ways to both educate and learn from the community is through role playing, which might contribute to changing of mind-sets when people realize the potential (positive and negative) consequences of their actions. Indeed, role playing is a way to mimic the actual processes playing out in the community in the course of water management decisions made over a long period of time. Socio-hydrologic models can thus facilitate but also benefit from such role playing. For example, *Wheater and Gober* [2015] report on activities within the Saskatchewan River Basin in Canada that connect research outputs to decision makers and the general public. One activity was a *Drought Tournament*, a workshop designed to enhance discussions among interdisciplinary groups about how to manage the immediate and longer-term effects of droughts, including asking participants to consider trade-offs associated with different mitigation options. Another is an interactive play based on stakeholder perspectives on downstream consequences of a flood from an irrigated farm upstream all the way to a village in the river delta. The play conveyed the complex context for flood management decision making, using science-based flood scenarios, which called upon the audience's values, emotions, and attitudes about flood risk for mitigation strategies, policy reform, and adjudicating among competing interests. To be truly effective for long-term planning, however, such role playing must include actors or stakeholders who transcend past and future generations (grandparents to grand-children) so that they reflect on process interactions and changing values and expectations over century time scales [*Loucks*, 2000]. The same applies to spatial processes, involving stakeholders who transcend the locality/project to represent preferences or values on regional, national, and global scales.

Socio-hydrological models can also assist in communicating to and educating the public, via various forms of the media, about the likely consequences of their decisions or actions. For example, it can facilitate stakeholder discussion of difficult choices, and enables sensitivity analysis and vulnerability assessments. Figure 11 is an example of the use of scenario analysis using stakeholder engagement. An exploratory socio-hydrological model was used to explore system vulnerabilities of and policy options for the Saskatchewan River Basin in Canada. Figure 11a presents the causal loop diagram for the model implemented in the basin. The model was used to evaluate trade-offs between investments in irrigated agriculture versus hydropower generation. Figure 11b presents summary results of outcomes for several what-if scenarios, which shows that increasing the amount of acreage for irrigated agriculture increases the net benefits to agriculture with relatively small reductions in the net benefits to hydropower. These model results helped to facilitate stakeholder discussion through making the cause-effect relationships transparent to the stakeholders [*Hassanzadeh et al*., 2014]. The model results may be particularly instructive for the discussions if emergent phenomena such as regime changes, tipping points or lock-ins are simulated that may not be apparent from inspection of the component processes.

5.2. Exploring Alternative Futures: *Possibility Space*

One of the potential uses of a fully configured socio-hydrologic model in a water resources context is predicting the possible outcomes of alternative decisions or choices in the form of a *possibility space* of alternative futures [*Pahl-Wostl*, 2002; *Blöschl and Montanari*, 2010]. Identifying alternative futures can play an important role in the decision making process [e.g., *Laurent et al*., 2015]. These are not necessarily the most likely futures but do provide insights about the system dynamics.

An example of the possibility space of the economic evolution over centuries of a community subject to flooding is shown in Figure 12. The panels are ordered by collective memory (horizontally) and risk-taking attitude (vertically). The results are based on a generic socio-hydrology model that represents feedbacks between the economic, political, technological, and hydrological processes within that community (Figure 9a). These processes operate at different time scales with the fastest scales being the floods and the slowest scales being the political processes of land use planning. The results suggest that combinations of a long memory (like elephants) and risk aversion (like rabbits) (top left in the figure) will lead to immediate economic collapse due to lost economic opportunities. This is due to people choosing settlement patterns far away from the river (as their memory of past floods is still in their minds) which will impact negatively on trade revenues. Combinations of a short memory (like cicadas) and a risk taking attitude (like lions) (bottom right) will also lead to rapid economic collapse due to persistent flood damages the community suffers over a long period as they choose to settle close to the river. More moderate parameter combinations in the model (reflecting more moderate attitudes of the community) will lead to more favorable outcomes including a set of parameter combinations in the middle of the figure which will always lead to fast economic growth.

The paths in each part of Figure 12 have all been obtained by a deterministic socio-hydrologic model with the same parameter set, assuming the same upstream flood frequency curve as a stochastic driver. The paths differ only in terms of the sequence in which the floods occur. For some parameter combinations, the paths are indeed extremely different. The part highlighted by the red asterisk shows an example of a bimodal distribution of wealth, i.e., depending on the sequence of the floods, the economy may either grow or weaken, and the intermediate cases are less likely. The path dependence is characteristic of complex systems [*Norton et al*., 1998]. It is also consistent with evidence from environmental history. For example, buildings typically were abandoned after multiple consecutive floods in a short time (e.g., relocation of the fifteenth century Franciscan friary in Visegrád, Hungary [*Kiss and Laszlovszky*, 2013]), while single exceptional floods were less likely to lead to their abandonment.

Out of the variety of model types that are in existence, comprehensive models [e.g., *Yaeger et al*., 2014; *Evans and Kelley*, 2004] have clear advantages when place-based solutions tailored to the local situation are of interest. On the other hand, stylized models [e.g., *Anderies*, 2000] may provide more transparent insight into the long-term system dynamics such as the conditions that may lead to critical transitions. Such models

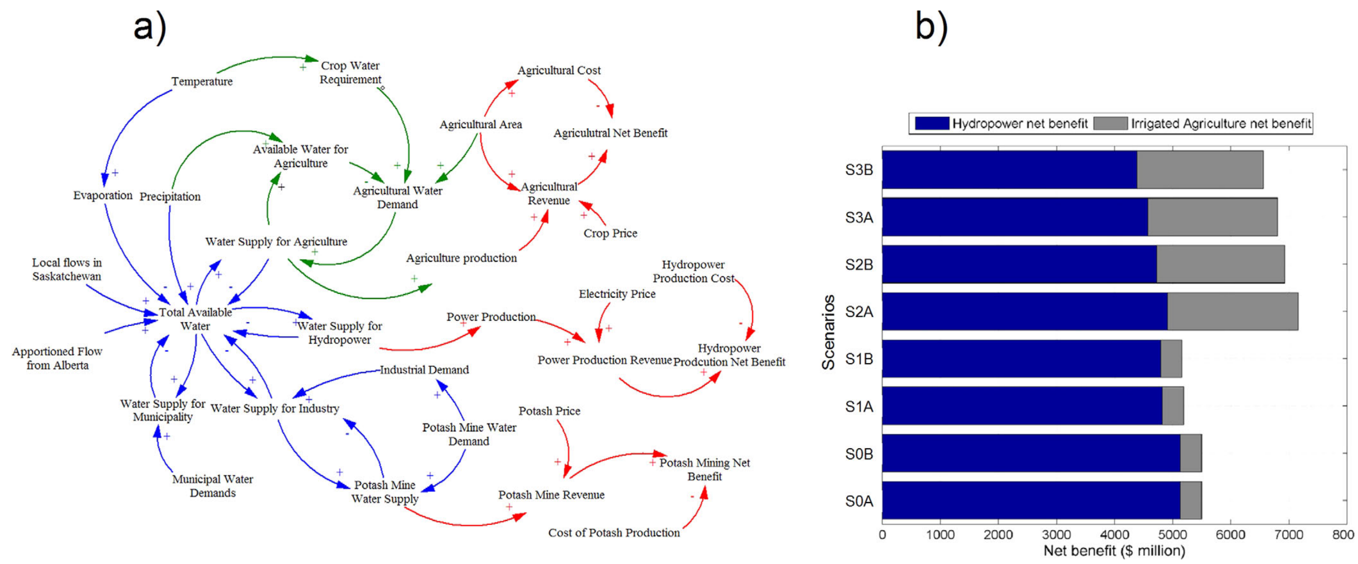

Figure 11. (a) Causal Loop Diagram for the SWAMP model for Saskatchewan River Basin, Canada; (b) economic evaluation of water for hydropower and irrigated agriculture for several what-if scenarios (using two different ET routines, A, B): S0—historical flows with baseline irrigation area; S1—5–8.5% drop in outflows from Alberta and baseline irrigation area; S2—historical flows and a fivefold increase in irrigation area; S3—a combination of both the above changes. From *Hassanzadeh et al.* [2014].

may give early-warning signs of imminent catastrophic changes, as illustrated by the Wonderland example in Figure 5. Equally important, a coevolutionary perspective may help with managing complex adaptive human-water systems in a sustainable way, since sustainability is perceived as a dynamic rather than a static property of the system [*Rammel et al.*, 2007]. The goal is to avoid unfavorable states rather than to converge to one stable optimum. Unfavorable states may include system lock-ins.

Indeed, sustainable water management in a dynamic world requires social learning and adaptive management [*Pahl-Wostl*, 2002]. *Walker et al.* [2015] present ways for including social responses dynamically into water resources planning decisions with the use of socio-hydrologic models. Socio-hydrologic models may represent changing preferences and values of the community [*Di Baldassarre et al.*, 2015; *Elshafei et al.*, 2015] in addition to the dynamics of the environment, technology, demography, economy, and governance in a quantitative way. It may not always be easy to estimate the parameters of such models for a particular case, and the nonlinear nature of the models will usually result in many possible system traces for the future [*Zehe et al.*, 2010; *Viglione et al.*, 2014]. However, exploring the possibility space with a view of avoiding bad choices rather than identifying optimum choices may be more conducive for sustainable management under uncertainty. This implies a shift from optimality to robustness [*Anderies et al.*, 2004], and a shift toward vulnerability and resilience centered management. Figure 13 illustrates the concept for the case of flood risk management in a changing world. The top-down approach (Figure 13, left) starts from projected future scenarios which feed into a cascade of models (from GCMs to downscaling, hydrological models, inundations and damage estimation). This approach is conceptually appealing as it mimics the main process causality and strives for economic optimality, but the probabilities used in this approach may be difficult to estimate, in particular in a coevolutionary world.

On the other hand, the bottom-up approach (Figure 13, right) starts directly from the vulnerability of the communities in question. The failure of the flood system in the example could be caused by many different factors and the traditional rainfall-to-flood transformation is only one of them. The system may also fail due to geotechnical reasons (percolation, internal erosion, burrowing animals), landslides, avalanches, poor construction, poor management, sabotage, and impact of war. The focus is thus less on causality and more on consequences. The method is “messier” involving methods that are less clearly structured, but it has a social motivation and is more amenable to accounting for surprises as it strives for reduced vulnerability and increased resilience [*Merz et al.*, 2015]. Imaginable surprises can be represented by “wildcards” to explore their consequences for the socio-hydrologic system [*Wardekker et al.*, 2010]. The bottom-up approach thus has an important and creative role for hydrologists to engage in explorative socio-hydrologic modeling to assist local risk managers and stakeholders in defining policy options.

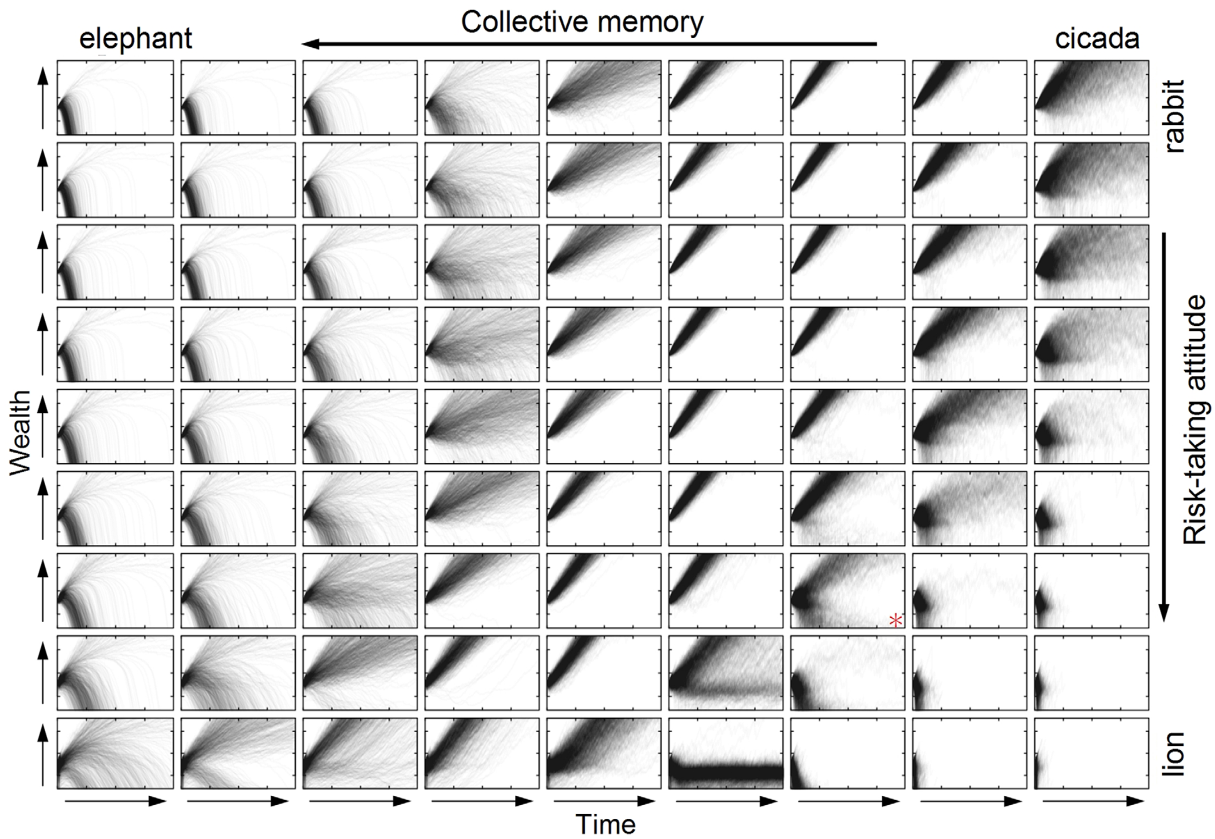

Figure 12. Possibility space: each part shows the evolution of the wealth of a community over scaled time (a few centuries). Grey shades indicate the probability of a particular path. Parts are ordered from right to left by decreasing collective memory and from top to bottom by increasing risk taking attitude. Part marked by asterisks shows a parameter combination that leads to a bimodal distribution of wealth due to path dependence. Adapted from *Viglione et al*. [2014].

5.3. Generalizing Beyond a Single Case Study

The third dimension by which we believe socio-hydrological models can assist with management is to learn from the experiences of other similar places, and move toward generalizations beyond individual case studies.

Two seemingly disparate water management situations can, on careful analysis, show strong similarities. For example, the complex situation experienced in Central Valley in California [*Fox et al*., 2015] has much similarity with the situation in the Heihe Basin in western China [*Gao et al*., 2014b]. Both watersheds are fed by snowmelt (and rainfall) in the headwaters, both contain a large middle section where much of the water (both surface water and groundwater) is used for irrigated agriculture, and societies in both basins are seriously concerned about consequent reductions in flow downstream. In California, the downstream consists of precious ecosystems in the San Francisco estuary, whereas Heihe basin is endorheic and the concern is the drying of the terminal lake. There are of course, important differences in the institutional set-ups and cultures but contrasting these cases may help appreciate the specifics and the more general findings for each case. These similarities and differences can be brought out through parallel framing of the two case studies as socio-hydrological models (see section 4). This parallel framing is particularly useful for emergent phenomena such as regime shifts, tipping points, and lock-ins.

Generalizations will benefit from the availability of long-term data sets on human-water system behavior. *Braden et al*. [2009] and *Vogel et al*. [2015] highlight the need for national-scale surveys and data sets of water use behavior and attitudes across sectors, and outline the specific requirements of such an enterprise. Generalizations can also benefit from increasing availability of new kinds of data that are coming on stream with the advance of technology such as satellite nighttime lights [*Ceola et al*., 2014], human sensing data, and enhanced communication opportunities through social networks.

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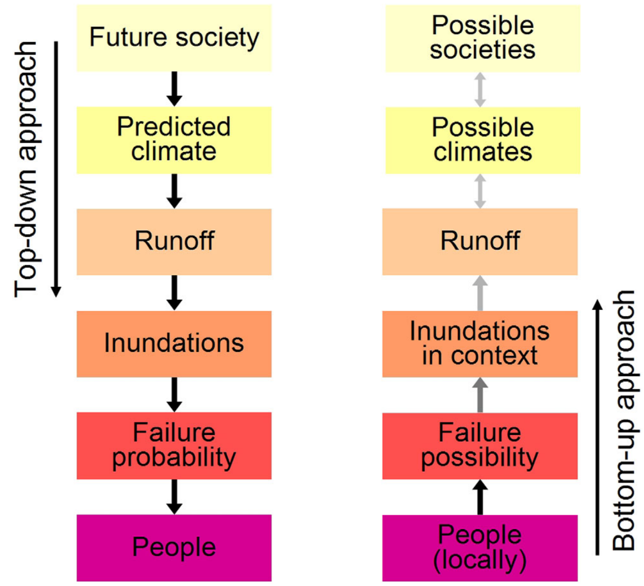

Figure 13. (left) Traditional top-down approach to hydrological risk assessment based on climate projections. (right) Bottom-up approach to hydrological risk assessment that is vulnerability or resilience centered. Approaches are illustrated by a fluvial flood risk example. Grey arrows indicate less dependence than black arrows. The top-down approach provides opportunities for normative socio-hydrologic modeling while the bottom-up approach provides opportunities for explorative socio-hydrologic modeling. From *Blöschl et al.* [2013b].

Of course, there exists already a substantial body of literature that deals with a large number of case studies [e.g., *Loucks et al.*, 2005; *Medema et al.*, 2008; *Bateman and Rancier*, 2012] or synthesizes findings from different studies by meta-analysis [e.g., *Srinivasan et al.*, 2012], but the framing by socio-hydrologic models in a quantitative way may provide added value. The comparative analysis of several case studies experiencing the same phenomena can give rise to generic models of the phenomena (e.g., irrigation efficiency paradox, levee effect, peak water paradox), which can accommodate differences in climatic and socio-economic political conditions [*Di Baldassarre et al.*, 2015; *Elshafei et al.*, 2015]. The availability of generic models enables fundamental studies of the behavior of socio-hydrologic systems in respect to each phenomenon. These are aimed at generating universal understanding that can help inform and educate both managers and the general public to anticipate problems in advance and develop a mix of solutions to consider in management. The benefit of more parsimonious stylized models is that they are more transparent and can be repeated more easily by peers, thus contributing to knowledge building [*Blöschl et al.*, 2014b]. They also help to organize scientific research that is aimed at isolating key socio-hydrologic processes and feedbacks and developing universal functional relationships that will go into models. This may help reduce the empirical nature of process descriptions in many socio-hydrologic models, thus making them universally applicable.

6. The Future of Socio-hydrology: Challenges and Opportunities

In this paper, we have presented a coevolutionary view of hydrologic systems for a changing world. Different aspects of the system are allowed to coevolve at different rates. This includes humans who are treated as endogenous to the system, not as mere boundary conditions. We have framed the resulting coupled human-nature system using a dynamical systems perspective, characterized by interactions between fast and slow processes, and feedbacks between a range of environmental and human/social processes. The distinguishing feature of this approach to hydrological science is the emphasis on time scale interactions. These give rise to the emergence of new, macroscale socio-hydrologic phenomena such as the levee effect, adaptation to change, and system collapse due to resource depletion. These phenomena are related to dynamical system concepts of path dependence, lock-ins, critical transitions, and multiple equilibria. The proposed coevolutionary view emphasizes a long-term perspective of hydrological systems in which dynamically changing human values play a fundamental role.

Here we propose a range of socio-hydrologic research questions that, we hope, will help further energize hydrologic science for the future.

a. Understanding human-water interactions
   1. Are there time scale interactions that are typical of human-water system behavior? Can slow and fast processes of the environment, technology, economics, and institutions be identified? What are the generic principles underlying the occurrence of emergent behavior in such systems? What is the role of path dependency and lock-ins?
   2. How do the human values embedded within water systems change in time? What are the causal factors for the change in values, and what are their effects on other system components? What is the effect of "irrationality" of human decisions on system behavior?
   3. What is the scaling behavior of human-water systems, i.e., how do dynamics at the scale of individuals, communities, and regions combine to produce aggregate behavior at larger scales? What is the role of the level of organization of the human-water system in this scaling behavior?
   4. How do human-water systems respond and interact with climate fluctuations at different time and space scales? In what way does the clustering of floods and droughts into separate decades affect the collective system behavior?
b. Modeling human-water interactions
   1. What is the appropriate model detail (stylized, comprehensive, or intermediate) for a particular socio-hydrological problem? How can model detail be reduced to increase their transparency without losing the richness of the dynamics? How can we use a mix of stylized and comprehensive models to test hypotheses on the human-water system?
   2. What are efficient strategies for identifying the parameters and functional relationships of socio-hydrological models? How can one deal with the inter-dependencies of the model parameters? What proxies can be used in the parameter estimation?
   3. How can system descriptions be generalized beyond individual case studies in order to discover universal principles underlying human-water interactions? How can the legacy of human-water systems observed now be used to reconstruct the coevolutionary history through space-time substitution? What insights can we gain from ancient societies that are still relevant for today?
   4. How can we benefit from new data opportunities related to human-water systems such as human sensing and social networks? How can we make inferences from large data sets such as nightlights?
c. Managing human-water interactions
   1. How can a coevolutionary view of human-water systems assist in water resources management? What is the specific role of time scale interactions in supporting long-term-strategic decision making? How can potential future changes in human values, as represented in socio-hydrological models, be exploited for decision making?
   2. How can coevolutionary models of coupled human-water systems complement the scenario approach used currently? What is their role in adaptive water management and social learning?
   3. What are early-warning signs of potential abrupt changes in human-water system behavior? How can the relevance of such signs be communicated?
   4. How can a coevolutionary view of human-water systems contribute to identifying robust management options (that are not necessarily optimal)? What are strategies to stay away from potential tipping points and lock-ins?

The perspective presented in this paper has followed the inter-disciplinary view that *Water Resources Research* has so effectively fostered over the last fifty years. The paper has attempted to move this view forward to a new coevolutionary view that accounts for the rapid and widespread changes brought about by human impacts on the hydrologic cycle and the need for longer lead times for strategic water resources planning. In doing so, the paper has emphasized the critical importance of studying changing water systems in the emergent Anthropocene through the lens of time scale interactions, and has articulated the vision that, in the context of these dynamic changes, hydrologic science and water resources management should be considered as two sides of the same coin.

Appendix A

Table A1 below summarizes the model parameter values used to produce the "badlands" simulation results presented in section 2.4.

Table A1. Parameters of the Badland Model (Equation (2))

Symbol	Meaning	Parameter Value
x	Runoff deviation from mean (m/yr) (mean is 0.2 m/yr), fast variable	
Y	Soil depth deviation from mean (m) (mean is 2 m), slow variable	
t	Time (years)	
ε	Time scale separation	0.001
a	Negative inverse relaxation time of runoff times ε	-0.001 year^{-1}
b	Damping effect of soil depth on runoff fluctuations times ε	-0.00002 year^{-2}
c	Net erosive effect of runoff deviation on soil depth (negative difference between erosion and soil formation)	-0.005 with soil protection, -0.5 without soil protection
d	Negative inverse relaxation time of soil depth	-0.001 year^{-1}
σ_x	Random component representing rainfall variability times ε	$std.dev\ (\sigma_x) = 0.0001$ m/yr^2
σ_Y	Random component representing effect of land slips	$std.dev\ (\sigma_Y) = 0.02$ m/yr

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References

Abbott, M. B., J. C. Bathurst, J. A. Cunge, P. E. O'Connell, and J. Rasmussen (1986), An introduction to the European Hydrological System—Systeme Hydrologique European, ''SHE'', 1: History and philosophy of a physically-based, distributed modelling system, *J. Hydrol.*, *87*(1), 45–59.
Adamowicz, W., J. Louviere, and M. Williams (1994), Combining revealed and stated preference methods for valuing environmental amenities, *J. Environ. Econ. Manage.*, *26*(3), 271–292.
An, L. (2012), Modeling human decisions in coupled human and natural systems: Review of agent-based models, *Ecol. Model.*, *229*, 25–36, doi:10.1016/j.ecolmodel.2011.07.010.
Anderies, J. M. (2000), On modeling human behavior and institutions in simple ecological economic systems, *Ecol. Econ.*, *35*(3), 393–412.
Anderies, J. M., M. A. Janssen and E. Ostrom (2004), A framework to analyze the robustness of social-ecological systems from an institutional perspective [online], *Ecol. Soc.*, *9*(1), Article 18. [Available at http://www.ecologyandsociety.org/vol9/iss1/art18.]
Baker, T. J., B. Cullen, L. Debevec, and Y. Abebe (2015), A socio-hydrological approach for incorporating gender into biophysical models and implications for water resources research, *Appl. Geogr.*, *62*, 325–338, doi:10.1016/j.apgeog.2015.05.008.
Bakker, K. (2012), Water security: Research challenges and opportunities, *Science*, *337*(6097), 914–915.
Band, L. E., and C. Tague (2005), Feedbacks and coupling between water, carbon and nutrient cycling at the hillslope scale, in *Coupled Models for the Hydrological Cycle-Integrating Atmosphere, Biosphere, and Pedosphere*, edited by A. Bronstert et al., pp. 269–278, Springer, N. Y.
Bateman, B., and R. Rancier (2012), *Case Studies in Integrated Water Resources Management: From Local Stewardship to National Vision*, 60 pp., Am. Water Resour. Assoc., Middleburg, Va.
Beck, M. B. (1999), Coping with ever larger problems, models, and data bases, *Water Sci. Technol.*, *39*(4), 1–11.
Becker, G. S. (1962), Irrational behavior and economic theory, *J. Polit. Econ.*, *70*, 1–13.
Berglund, N., and B. Gentz (2006), *Noise-Induced Phenomena in Slow-Fast Dynamical Systems: A Sample-Paths Approach*, 276 pp., Springer, London, U. K.
Beven, K. (1989), Changing ideas in hydrology—The case of physically-based models, *J. Hydrol.*, *105*(1), 157–172.
Beven, K. (2015), What we see now: Event-persistence and the predictability of hydro-eco-geomorphological systems, *Ecol. Model.*, *298*, 4–15, doi:10.1016/j.ecolmodel.2014.07.019.
Beven, K. J. and M. J. Kirkby (1979), A physically based, variable contributing area model of basin hydrology, *Hydrol. Sci. Bull.*, *24*(1), 43–69, doi:10.1080/02626667909491834.
Blöschl, G., and A. Montanari (2010), Climate change impacts—Throwing the dice?, *Hydrol. Processes*, *24*, 374–381, doi:10.1002/hyp.7574.
Blöschl, G., and M. Sivapalan (1995), Scale issues in hydrological modelling—A review, *Hydrol. Processes*, *9*(3/4), 251–290.
Blöschl, G., M. Sivapalan, V. K. Gupta, K. Beven, and D. Lettenmaier (1997), Preface to the special section on scale problems in hydrology, *Water Resour. Res.*, *33*, 2881–2881.
Blöschl, G., M. Sivapalan, T. Wagener, A. Viglione, and H. H. G. Savenije (Eds.) (2013a), *Runoff Prediction in Ungauged Basins—Synthesis Across Processes, Places and Scales*, 465 pp., Cambridge Univ. Press, Cambridge, U. K.
Blöschl, G., A. Viglione, and A. Montanari (2013b), Emerging approaches to hydrological risk management in a changing world, in *Climate Vulnerability: Understanding and Addressing Threats to Essential Resources*, edited by R. Pielke, pp. 3–10, Academic Press, Amsterdam, Netherlands.
Blöschl, G., H. Thybo, and H. H. G. Savenije (2014a), *A Voyage Through Scales: The Earth System in Space and Time*, 120 pp., Eur. Geosci. Union, Bonn, Germany.
Blöschl, G., A. B. Bárdossy, D. Koutsoyiannis, Z. W. Kundzewicz, I. Littlewood, A. Montanari, and H. Savenije (2014b), On the future of journal publications in hydrology, *Water Resour. Res.*, *50*, 2795–2797, doi:10.1002/2014WR015613.
Braden, J. B., et al. (2009), Social science in a water observing system, *Water Resour. Res.*, *45*, W11301, doi:10.1029/2009WR008216.
Brandt, G., and A. Merico (2015), The slow demise of Easter Island: Insights from a modeling investigation, *Frontiers Ecol. Evol.*, *3*, 13.
Brouwer, R., and R. Van Ek (2004), Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands, *Ecol. Econ.*, *50*(1), 1–21.
Brown, C. M., J. R. Lund, X. Cai, P. M. Reed, E. A. Zagona, A. Ostfeld, J. Hall, G. W. Characklis, W. Yu, and L. Brekke (2015), The future of Water Resources Systems analysis: Toward a scientific framework for sustainable water management, *Water Resour. Res.*, doi:10.1002/2015WR017114, in press.
Brun, R., P. Reichert, and H. R. Künsch (2001), Practical identifiability analysis of large environmental simulation models, *Water Resour. Res.*, *37*(4), 1015–1030.
Bruna, M., S. J. Chapman, and M. J. Smith (2014), Model reduction for slow-fast stochastic systems with metastable behaviour, *J. Chem. Phys.*, *140*(17), 174107, doi:10.1063/1.4871694.
Burningham, K., J. Fielding, and D. Thrush (2008), 'It'll never happen to me': Understanding public awareness of local flood risk, *Disasters*, *32*(2), 216–238.

Cai, X., D. C. McKinney, and L. S. Lasdon (2002), A framework for sustainability analysis in water resources management and application to the Syr Darya Basin, *Water Resour. Res.*, *38*(6), 1085, doi:10.1029/2001WR000214.

Cai, X., R. Zeng, W. H. Kang, J. Song, and A. J. Valocchi (2015), Strategic planning for drought mitigation under climate change, *J. Water Resour. Plann. Manage.*, doi:10.1061/(ASCE)WR.1943–5452.0000510, in press.

Caldas, M. M., et al. (2015), Opinion: Endogenizing culture in sustainability science research and policy, *Proc. Natl. Acad. Sci. U. S. A.*, *112*(27), 8157–8159, doi:10.1073/pnas.1510010112.

Carr, G., G. Blöschl, and D. P. Loucks (2012), Evaluating participation in water resource management: A review, *Water Resour. Res.*, *48*, W11401, doi:10.1029/2011WR011662.

Carr, G., D. P. Loucks and G. Blöschl (2013), An analysis of public participation in the Lake Ontario-St. Lawrence River study, in *Water Co-Management*, edited by V. I. Gover and G. Kratzenberg, pp. 48–77, CRC Press, Boca Raton, Fla.

Ceola, S., F. Laio, and A. Montanari (2014), Satellite nighttime lights reveal increasing human exposure to floods worldwide, *Geophys. Res. Lett.*, *41*, 7184–7190, doi:10.1002/2014GL061859.

Chamberlin, T. C. (1965), The method of multiple working hypotheses, *Science*, *15*, 754–759, doi:10.1126/science.148.3671.754.

Charney, J. G. (1948), On the scale of atmospheric motions, *Geophys. Publ.*, *17*, 1–17.

Chen, X., D. Wang, F. Tian, and M. Sivapalan (2014), Understanding socio-hydrology system in the Kissimmee River Basin, Abstract H41D-0840 presented at 2014 Fall Meeting, AGU, San Francisco, Calif.

Corenblit, D., A. M. Gurnell, J. Steiger, and E. Tabacchi (2008), Reciprocal adjustments between landforms and living organisms: Extended geomorphic evolutionary insights, *Catena*, *73*(3), 261–273.

Corenblit, D., A. C. Baas, G. Bornette, J. Darrozes, S. Delmotte, R. A. Francis, A. M. Gurnell, F. Julien, R. J. Naiman, and J. Steiger (2011), Feedbacks between geomorphology and biota controlling Earth surface processes and landforms: A review of foundation concepts and current understandings, *Earth Sci. Rev.*, *106*(3), 307–331.

Crawford, N. H., and R. K. Linsley (1966), Digital simulation in hydrology: Stanford watershed model IV, *Tech. Rep. 39*, 210 pp., Dep. of Civ. Eng., Stanford Univ., Stanford, Calif.

Culp, P. W., R. J. Glennon, and G. Libecap (2014), Shopping for water: How the market can mitigate water shortages in the American West, *Discuss. Pap. 2014-05*, 36 pp., Stanford Woods Inst. for the Environ.

Cumming, G. S., D. H. Cumming, and C. L. Redman (2006), Scale mismatches in social-ecological systems: Causes, consequences, and solutions [online], *Ecol. Soc.*, *11*(1), Article 14. [Available at http://www.ecologyandsociety.org/vol11/iss1/art14/.]

Dawson, R. J., R. Peppe, and M. Wang (2011), An agent-based model for risk-based flood incident management, *Nat. Hazards*, *59*, 167–189, doi:10.1007/s11069-011-9745-4.

Di Baldassarre, G. (2015), Interactive comment on "Moving sociohydrology forward: A synthesis across studies" by T. J. Troy et al., *Hydrol. Earth Syst. Sci. Discuss.*, *12*, C1357–C1361.

Di Baldassarre, G., M. Kooy, J. S. Kemerink, and L. Brandimarte (2013a), Towards understanding the dynamic behaviour of floodplains as human-water systems, *Hydrol. Earth Syst. Sci.*, *17*(8), 3235–3244, doi:10.5194/hess-17–3235-2013.

Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, J. L. Salinas, and G. Blöschl (2013b), Socio-hydrology: Conceptualising human-flood interactions, *Hydrol. Earth Syst. Sci.*, *17*, 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*, 4770–4781, doi:10.1002/2014WR016416.

Dooge, J. C. I. (1955), *Linear Theory of Hydrological Systems, U.S. Dep. Agric. Tech. Bull. 1468*, 327 pp., U.S. Gov. Print. Off., Washington, D. C.

Dooge, J. C. I. (1986), Looking for hydrologic laws, *Water Resour. Res.*, *22*, 46S–58S.

Dunning, N. P., T. P. Beach, and S. Luzzadder-Beach (2012), Kax and Kol: Collapse and resilience in lowland Maya civilization, *Proc. Natl. Acad. Sci. U. S. A.*, *109*, 3652–3657.

Eagleson, P. S. (1982), Ecological optimality in water-limited natural soil-vegetation systems: 1. Theory and hypothesis, *Water Resour. Res.*, *18*, 325–340.

Ehrlich, P. R., and P. H. Raven (1964), Butterflies and plants: A study in coevolution, *Evolution*, *18*, 586–608.

Elshafei, Y., M. Sivapalan, M. Tonts, and M. L. Hipsey (2014), A prototype framework for models of socio-hydrology: Identification of key feedback loops and parameterisation approach, *Hydrol. Earth Syst. Sci.*, *18*, 2141–2166, doi:10.5194/hess-18–2141-2014.

Elshafei, Y., M. Sivapalan, J. Z. Coletti, and M. R. Hipsey (2015), A model of the socio-hydrologic dynamics in a semi-arid catchment: Isolating feedbacks in the coupled human-hydrology system, *Water Resour. Res.*, doi:10.1002/2015WR017048, in press.

European Union (2000), Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Communities in the field of water policy, *Off. J. Eur. Commun.*, *L 327*, 1–73.

Evans, T. P., and H. Kelley (2004), Multi-scale analysis of a household level agent-based model of landcover change, *J. Environ. Manage.*, *72*(1), 57–72.

Fox, P., P. H. Hutton, D. J. Howes, A. J. Draper, and L. Sears (2015), Reconstructing the natural hydrology of the San Francisco Bay-Delta watershed, *Hydrol. Earth Syst. Sci. Discuss.*, *12*(4), 3847–3892.

Freeze, R. A., and R. L. Harlan (1969), Blueprint for a physically-based, digitally-simulated hydrologic response model, *J. Hydrol.*, *9*(3), 237–258.

Gaál, L., J. Szolgay, S. Kohnová, J. Parajka, R. Merz, A. Viglione, and G. Blöschl (2012), Flood timescales: Understanding the interplay of climate and catchment processes through comparative hydrology, *Water Resour. Res.*, *48*, W04511, doi:10.1029/2011WR011509.

Gao, H., M. Hrachowitz, S. J. Schymanski, F. Fenicia, N. Sriwongsitanon and H. H. G. Savenije (2014a), Climate controls how ecosystems size the root zone storage capacity at catchment scale, *Geophys. Res. Lett.*, *41*, 7916–7923, doi:10.1002/2014GL061668.

Gao, H., M. Hrachowitz, F. Fenicia, S. Gharari, and H. H. G. Savenije (2014b), Testing the realism of a topography-driven model (FLEX-Topo) in the nested catchments of the Upper Heihe, China, *Hydrol. Earth Syst. Sci.*, *18*, 1895–1915, doi:10.5194/hess-18–1895-2014.

Geels, F. W. (2005), Processes and patterns in transitions and system innovations: Refining the co-evolutionary multi-level perspective, *Technol. Forecast. Soc. Change*, *72*(6), 681–696.

Gladwell, M. (2006), *The Tipping Point: How Little Things Can Make a Big Difference*, 301 pp., Little, Brown & Co., Boston, Mass.

Gleick, P. H. (2000), A look at twenty-first century water resources development, *Water Int.*, *25*(1), 127–138.

Gober, P., D. D. White, R. Quay, D. A. Sampson, and C. W. Kirkwood (2014), Socio-hydrology modelling for an uncertain future, with examples from the USA and Canada, in *Integrated Environmental Modelling to Solve Real World Problems: Methods, Vision and Challenges*, edited by A. T. Riddick, H. Kessler, and J. R. A. Giles, *Geol. Soc. Spec. Publ., 408*, doi:10.1144/SP408.2.

Gorelick, S. M., and C. Zheng (2015), Global change and the groundwater management challenge, *Water Resour. Res.*, *51*, 3031–3051, doi:10.1002/2014WR016825.

Grayson, R. B., and G. Blöschl (Eds.) (2000), *Spatial Patterns in Catchment Hydrology: Observations and Modelling*, 404 pp., Cambridge Univ. Press, Cambridge, U. K.

Gröller, E., R. Wegenkittl, A. Milik, A. Prskawetz, and G. Feichtinger (1996), Geometry of Wonderland, *Chaos Solitons Fractals*, *7*(12), 1989–2006.

Gunderson, L. H., C. S. Holling, and S. S. Light (1995), *Barriers and Bridges to the Renewal of Ecosystems and Institutions*, 593 pp., Columbia Univ. Press, N. Y.

Hall, J., et al. (2014), Understanding flood regime changes in Europe: A state of the art assessment, *Hydrol. Earth Syst. Sci.*, *18*(7), 2735–2772.

Hassanzadeh, E., A. Elshorbagy, H. S. Wheater, and P. Gober (2014), Managing water in complex systems: An integrated water resources model for Saskatchewan, Canada, *Environ. Model. Software*, *58*, 12–26, doi:10.1016/j.envsoft.2014.03.015.

Hipsey, M. R., D. P. Hamilton, P. C. Hanson, C. C. Carey, J. Z. Coletti, J. S. Read, B. W. Ibelings, F. Valesini, and J. D. Brookes (2015), Predicting the resilience and recovery of aquatic systems: A framework for model evolution within environmental observatories, *Water Resour. Res.*, doi:10.1002/2015WR017175, in press.

Hofbauer, J., and K. Sigmund (1988), *The Theory of Evolution and Dynamical Systems*, 341 pp., Cambridge Univ. Press, Cambridge, U. K.

Holling, C. S. (2001), Understanding the complexity of economic, ecological, and social systems, *Ecosystems*, *4*(5), 390–405.

Hooke, J. (2003), River meander behaviour and instability: A framework for analysis, *Trans. Inst. Br. Geogr.*, *28*, 238–253, doi:10.1111/1475–5661.00089.

Horton, R. E. (1933), The role of infiltration in the hydrologic cycle, *Trans. AGU*, *14*, 446–460.

Ikeda, S., and G. Parker (1989), *River Meandering*, AGU, Washington, D. C., doi:10.1029/WM012p0181.

Jakeman, A. J., R. A. Letcher, and J. P. Norton (2006), Ten iterative steps in development and evaluation of environmental models, *Environ. Model. Software*, *21*(5), 602–614.

Kalma, J. D., and M. Sivapalan (1995), *Scale Issues in Hydrological Modelling*, 504 pp., John Wiley, Chichester, U. K.

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

Kiss, A., and J. Laszlovszky (2013), 14th-16th-century Danube floods and long-term water-level changes in archaeological and sedimentary evidence in the western and central Carpathian Basin: An overview with documentary comparison, *J. Environ. Geogr.*, *6*(3-4), 1–11.

Kleidon, A., and S. J. Schymanski (2008), Thermodynamics and optimality of the water budget on land: A review, *Geophys. Res. Lett.*, *35*, L20404, doi:10.1029/2005GL025373.

Kolmogoroff, A. (1931), Über die analytischen Methoden in der Wahrscheinlichkeitsrechnung, *Math. Ann.*, *104*, 415–458.

Krantzberg, G., I. F. Creed, K. B. Friedman, K. L. Laurent, J. A. Jackson, J. Brammeier, and D. Scavia (2015), Community engagement is critical to achieve a "thriving and prosperous" future for the Great Lakes–St. Lawrence River basin, *J. Great Lakes Res.*, *41*, 188–191.

Kuehn, C. (2011), A mathematical framework for critical transitions: Bifurcations, fast–slow systems and stochastic dynamics, *Physica D*, *240*(12), 1020–1035.

Kuehn, C. (2015), *Multiple Time Scale Dynamics, Appl. Math. Sci. Ser.*, vol. 191, 814 pp., Springer, N. Y.

Kumar, M., C. J. Duffy, and K. M. Salvage (2009), A second-order accurate, finite volume–based, integrated hydrologic modeling (FIHM) framework for simulation of surface and subsurface flow, *Vadose Zone J.*, *8*(4), 873–890.

Lade, S. J., A. Tavoni, S. A. Levin, and M. Schlüter (2013), Regime shifts in a social-ecological system, *Theor. Ecol.*, *6*(3), 359–372.

Laurent, K. L., D. Scavia, K. B. Friedman, G. K. Krantzberg, and I. F. Creed (2015), Critical forces defining alternative futures for the Great Lakes–St. Lawrence River basin, *J. Great Lakes Res.*, *41*, 131–138.

Liu, D., F. Tian, M. Lin, and M. Sivapalan (2015), A conceptual socio-hydrological model of the co-evolution of humans and water: Case study of the Tarim River basin, western China, *Hydrol. Earth Syst. Sci.*, *19*, 1035–1054, doi:10.5194/hess-19–1035-2015.

Liu, J., et al. (2007a), Complexity of coupled human and natural systems, *Science*, *317*, 1513–1516.

Liu, J., et al. (2007b), Coupled human and natural systems, *Ambio*, *36*, 639–649.

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. (1977), An application of interactive multi-objective water resources planning, *Interfaces*, *8*(1), 70–75.

Loucks, D. P. (2000), Sustainable water resources management, *Water Int.*, *25*(1), 3–10.

Loucks, D. P., E. Van Beek, J. R. Stedinger, J. P. Dijkman, and M. T. Villars (2005), *Water Resources Systems Planning and Management: An Introduction to Methods, Models and Applications*, 680 pp., UNESCO, Paris.

Lu, Z., Y. Wei, H. Xiao, S. Zou, J. Xie, J. Ren, and A. Western (2015), Evolution of the human–water relationships in the Heihe River basin in the past 2000 years, *Hydrol. Earth Syst. Sci.*, *19*, 2261–2273, doi:10.5194/hess-19–2261-2015.

Lucero, L. J. (2002), The collapse of the classic Maya: A case for the role of water control, *Am. Anthropol.*, *104*, 814–826.

Lutz, W., and K. C. Samir (2010), Dimensions of global population projections: What do we know about future population trends and structures?, *Philos. Trans. R. Soc. B*, *365*(1554), 2779–2791.

Maass, A., M. M. Hufschmidt, R. Dorfman, H. A. Thomas Jr., S. A. Marglin, and G. M. Fair (1962), *Design of Water-Resource Systems: New Techniques for Relating Economic Objectives, Engineering Analysis, and Governmental Planning*, 620 pp., Harvard Univ. Press, Cambridge, Mass.

Marston, R. A. (2010), Geomorphology and vegetation on hillslopes: Interactions, dependencies, and feedback loops, *Geomorphology*, *116*(3), 206–217.

McDonald, J. F. (1989), Econometric studies of urban population density: A survey, *J. Urban Econ.*, *26*, 361–385.

Medema, W., B. S. McIntosh, and P. J. Jeffrey (2008), From premise to practice: A critical assessment of integrated water resources management and adaptive management approaches in the water sector [online], *Ecol. Soc.*, *13*(2), Article 29. [Available at http://www.ecologyandsociety.org/vol13/iss2/art29/.]

Merz, B., J. Hall, M. Disse, and A. Schumann (2010), Fluvial flood risk management in a changing world, *Nat. Hazards Earth Syst. Sci.*, *10*(3), 509–527.

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 Resour. Res.*, doi:10.1002/2015WR017464, in press.

Milik, A., A. Prskawetz, G. Feichtinger, and W. C. Sanderson (1996), Slow-fast dynamics in Wonderland, *Environ. Model. Assess.*, *1*(1-2), 3–17.

Monger, C., O. E. Sala, M. C. Duniway, H. Goldfus, I. A. Meir, R. M. Poch, H. L. Throop, and E. R. Vivoni (2015), Legacy effects in linked ecological–soil–geomorphic systems of drylands, *Frontiers Ecol. Environ.*, *13*(1), 13–19, doi:10.1890/140269.

Montanari, A., et al. (2013), "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022, *Hydrol. Sci. J.*, *58*(6), 1256–1275, doi:10.1080/02626667.2013.809088.

Morrison, M., J. Bennett, and R. Blamey (1999), Valuing improved wetland quality using choice modeling, *Water Resour. Res.*, *35*, 2805–2814, doi:10.1029/1999WR900020.

Noel, P. H. C. (2015), *Studying Coupled Human and Natural Systems From a Decentralized Perspective: The Case of Agent-Based and Decentralized Modeling*, MS thesis, 62 pp., Dep. of Civ. Environ. Eng., Univ. of Ill., Urbana.

Norgaard, R. (1994), *Development Betrayed: The End of Progress and a Coevolutionary Revisioning of the Future*, 296 pp., Routledge, London, U. K.

Norton, B., R. Costanza, and R. C. Bishop (1998), The evolution of preferences: Why 'sovereign' preferences may not lead to sustainable policies and what to do about it, *Ecol. Econ.*, *24*(2), 193–211.

O'Connell, P. E., and G. O'Donnell (2014), Towards modelling flood protection investment as a coupled human and natural system, *Hydrol. Earth Syst. Sci.*, *18*, 155–171, doi:10.5194/hess-18–155-2014.

Odum, W. E. (1982), Environmental degradation and the tyranny of small decisions, *BioScience*, *32*(9), 728–729, doi:10.2307/1308718.

Oreskes, N. (2015), How earth science has become a social science, *Hist. Soc. Res.*, *40*(2), 246–270.

Oreskes, N., K. Shrader-Frechette, and K. Belitz (1994), Verification, validation, and confirmation of numerical models in the earth sciences, *Science*, *263*(5147), 641–646.

Ostrom, E. (1990), An institutional approach to the study of self-organization and self-governance in CPR situations, pp. 29–57, in *Governing the Commons The Evolution of Institutions for Collective Action*, chap. 2, 298 pp., Cambridge Univ. Press, Cambridge, U. K.

Ostrom, E. (2009), A general framework for analyzing sustainability of social-ecological systems, *Science*, *325*, 419–422, doi:10.1126/science.1172133.

Oyama, M. D., and C. A. Nobre (2003), A new climate-vegetation equilibrium state for tropical South America, *Geophys. Res. Lett.*, *30*(23), 2199, doi:10.1029/2003GL018600.

Pahl-Wostl, C. (2002), Towards sustainability in the water sector—The importance of human actors and processes of social learning, *Aquat. Sci.*, *64*(4), 394–411.

Pande, S., and M. W. Ertsen (2014), Endogenous change: On cooperation and water availability in two ancient societies, *Hydrol. Earth Syst. Sci.*, *18*(5), 1745–1760.

Paola, C., E. Foufoula-Georgiou, W. E. Dietrich, M. Hondzo, D. Mohrig, G. Parker, M. E. Power, I. Rodriguez-Iturbe, V. Voller, and P. Wilcock (2006), Toward a unified science of the Earth's surface: Opportunities for synthesis among hydrology, geomorphology, geochemistry, and ecology, *Water Resour. Res.*, *42*, W03S10, doi:10.1029/2005WR004336.

Pelletier, J. D., et al. (2013), Coevolution of nonlinear trends in vegetation, soils, and topography with elevation and slope aspect: A case study in the sky islands of southern Arizona, *J. Geophys. Res. Earth Surf.*, *118*, 741–758, doi:10.1002/jgrf.20046.

Penny, D. (2014), Water Management at Angkor, in *Encyclopaedia of the History of Science, Technology, and Medicine in Non-Western Cultures*, pp. 1–5, Springer.

Perdigão, R. A. P., and G. Blöschl (2014), Spatiotemporal flood sensitivity to annual precipitation: Evidence for landscape-climate coevolution, *Water Resour. Res.*, *50*, 54925509, doi:10.1002/2014WR015365.

Peterson, T. J., R. M. Argent, A. W. Western, and F. H. S. Chiew (2009), Multiple stable states in hydrological models: An ecohydrological investigation, *Water Resour. Res.*, *45*, W03406, doi:10.1029/2008WR006886.

Phillips, J. D. (1995), Biogeomorphology and landscape evolution: The problem of scale, *Geomorphology*, *13*, 337–347.

Phillips, J. D. (2001), Contingency and generalization in pedology, as exemplified by texture-contrast soils, *Geoderma*, *102*(3), 347–370.

Phillips, J. D. (2007), The perfect landscape, *Geomorphology*, *84*(3), 159–169.

Phillips, J. D. (2015), The robustness of chronosequences, *Ecol. Model.*, *298*, 16–23.

Pickett, S. T. A. (1989), Space-for-time substitutions as an alternative to long term studies, in *Long-Term Studies in Ecology*, edited by G. E. Likens, pp. 110–135, Springer, N. Y.

Porder, S. (2014), Coevolution of life and landscapes, *Proc. Natl. Acad. Sci. U. S. A.*, *111*(9), 3207–3208.

Price, R. K. (1986), Flood routing, in *Developments in Hydraulic Engineering*, pp.129–173, edited by P. Novak, Elsevier, Amsterdam, Netherlands.

Rammel, C., S. Stagl, and H. Wilfing (2007), Managing complex adaptive systems—A co-evolutionary perspective on natural resource management, *Ecol. Econ.*, *63*(1), 9–21.

Reiners, P. W., T. A. Ehlers, S. G. Mitchell, and D. R. Montgomery (2003), Coupled spatial variations in precipitation and long-term erosion rates across the Washington Cascades, *Nature*, *426*(6967), 645–647.

Reinhardt, L., D. Jerolmack, B. J. Cardinale, V. Vanacker, and J. Wright (2010), Dynamic interactions of life and its landscape: Feedbacks at the interface of geomorphology and ecology, *Earth Surf. Processes Landforms 35(1), 78-101*.

Reis, H. T., and S. Sprecher (Eds.) (2009), *Encyclopedia of Human Relationships*, 1904 pp., Sage Publ., Thousand Oaks, Calif.

Rhoads, B. L., and C. E. Thorn (1996), Observation in geomorphology, in *The Scientific Nature of Geomorphology: Proceedings of 27th Binghamton Symposium in Geomorphology, 27–29 September, 1996*, vol. 27, pp. 21–56, John Wiley, Chichester, U. K.

Robinson, C. (1995), *Dynamical Systems: Stability, Symbolic Dynamics, and Chaos*, CRC Press, Boca Raton, Fla.

Rockström, J., M. Falkenmark, C. Folke, M. Lannerstad, J. Barron, E. Enfors, L. Gordon, J. Heinke, H. Hoff, and C. Pahl-Wostl (2014), *Water Resilience for Human Prosperity*, 311 pp., Cambridge Univ. Press, N. Y.

Rodriguez-Iturbe, I., A. Rinaldo, R. Rigon, R. L. Bras, A. Marani, and E. J. Ijjasz-Vasquez (1992), Fractal structures as least energy patterns: The case of river networks, *Geophys. Rev. Lett.*, *19*, 889–892, doi:10.1029/92GL00938.

Rodriguez-Iturbe, I., P. D'Odorico, A. Porporato, and L. Ridolfi (1999), On the spatial and temporal links between vegetation, climate, and soil moisture, *Water Resour. Res.*, *35*, 3709–3722, doi:10.1029/91WR03034.

Rogers, P. P., and M. B. Fiering (1986), Use of systems analysis in water management, *Water Resour. Res.*, *22*, 146S–158S.

Russell, C. S., and D. D. Baumann (Eds.) (2009), *The Evolution of Water Resource Planning and Decision Making*, 299 pp., Edward Elgar Publ., Cheltenham, U. K.

Saco, P. M., and M. Moreno-de las Heras (2013), Ecogeomorphic coevolution of semiarid hillslopes: Emergence of banded and striped vegetation patterns through interaction of biotic and abiotic processes, *Water Resour. Res.*, *49*, 115–126, doi:10.1029/2012WR012001.

Sanderson, M. R., and R. S. Frey (2015), Structural impediments to sustainable groundwater management in the High Plains Aquifer of western Kansas, *Agric. Human Values*, *32*, 401–417, doi:10.1007/s10460-014-9567-6.

Sanderson, W. C. (1994), Simulation models of demographic, economic, and environmental interactions, in *Population—Development—Environment*, pp. 33–71, Springer, N. Y.

Savenije, H. H. G., A. Y. Hoekstra, and P. van der Zaag (2014), Evolving water science in the Anthropocene, *Hydrol. Earth Syst. Sci.*, *18*, 319–332, doi:10.5194/hess-18–319-2014.

Scanlon, B. R., C. C. Faunt, L. Longuevergne, R. C. Reedy, W. M. Alley, V. L. McGuire, and P. B. McMahon (2012), Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley, *Proc. Natl. Acad. Sci. U. S. A.*, *109*(24), 9320–9325.

Scheffer, M. (2009), *Critical Transitions in Nature and Society*, 400 pp., Princeton Univ. Press, Princeton, N. J.

Scheffer, M., J. Bascompte, W. A. Brock, V. Brovkhin, S. R. Carpenter, V. Dakos, H. Held, E. H. van Nes, M. Rietkerk, and G. Sugihara (2009), Early-warning signals for critical transitions, *Nature*, *461*, 53–59.

Scheffer, M., et al. (2012), Anticipating critical transitions, *Science*, *338*, 344–348.

Scheidegger, A. E. (2004), *Morphotectonics*, 113 pp., Springer, Berlin.

Schilders, W. H., H. A. Van der Vorst, and J. Rommes (2008), *Model Order Reduction: Theory, Research Aspects and Applications*, vol. 13, 471 pp., Springer, Berlin.

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.

Schymanski, S. J., M. Sivapalan, M. L. Roderick, L. B. Hutley, and J. Beringer (2009), An optimality-based model of the dynamic feedbacks between natural vegetation and the water balance, *Water Resour. Res.*, *45*, W01412, doi:10.1029/2008WR006841.

Scott, C. A. (2011), The water-energy-climate nexus: Resources and policy outlook for aquifers in Mexico, *Water Resour. Res.*, *47*, W00L04, doi:10.1029/2011WR010805.

Simon, H. A. (1978), Rationality as process and as product of thought, *Am. Econ. Rev.*, *68*(2), 1–16.

Simon, H. A. (1986), Rationality in psychology and economics, *J. Business*, *59*, S209–S224.

Sivapalan, M. (2015), Debates—Perspectives in Socio-hydrology: Changing water systems and the "tyranny of small problems"—Socio-hydrology, *Water Resour. Res.*, *51*, 4795–4805, doi:10.1002/2015WR017080.

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

Sivapalan, M., M. Konar, V. Srinivasan, A. Chhatre, A. Wutich, C. A. Scott, J. L. Wescoat, and I. Rodriguez-Iturbe (2014), Socio-hydrology: Use-inspired water sustainability science for the Anthropocene, *Earth's Future*, *2*, 225–230, doi:10.1002/2013EF000164.

Skøien, J. O., G. Blöschl, and A. W. Western (2003), Characteristic space scales and timescales in hydrology, *Water Resour. Res.*, *39*(10), 1304, doi:10.1029/2002WR001736.

Srinivasan, V. (2015), Reimagining the past—Use of counterfactual trajectories in socio-hydrological modelling: The case of Chennai, India, *Hydrol. Earth Syst. Sci.*, *19*, 785–801, doi:10.5194/hess-19–785-2015.

Srinivasan, V., S. M. Gorelick, and L. Goulder (2010), A hydrologic-economic modeling approach for analysis of urban water supply dynamics in Chennai, India, *Water Resour. Res.*, *46*, W07540, doi:10.1029/2009WR008693.

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 Resour. Res.*, *48*, W10516, doi:10.1029/2011WR011087.

Srivastava, S. K., R. C. Srivastava, R. R. Sethi, A. Kumar, and A. K. Nayak (2014), Accelerating groundwater and energy use for agricultural growth in Odisha: Technological and policy issues, *Agric. Econ. Res. Rev.*, *27*(2), 259–270.

Ter Braak, C. J. F., and I. C. Prentice (1988), A theory of gradient analysis, *Adv. Ecol. Res.*, *18*, 271–317.

Therrien, R., R. G. McLaren, E. A. Sudicky, and S. M. Panday (2010), *HydroGeoSphere: A Three-Dimensional Numerical Model Describing Fully-Integrated Subsurface and Surface Flow and Solute Transport*, Groundwater Simul. Group, Univ. of Waterloo, Waterloo, Ontario, Canada.

Thompson, S. E., M. Sivapalan, C. J. Harman, V. Srinivasan, M. Hipsey, P. Reed, A. Montanari, and G. Blöschl (2013), Understanding and predicting changing water systems: Use-inspired hydrologic science for the Anthropocene, *Hydrol. Earth Syst. Sci.*, *17*, 5013–5039, doi:10.5194/hess-17–5013-2013.

Tidwell, V. C., H. D. Passell, S. H. Conrad, and R. P. Thomas (2004), System dynamics modeling for community-based water planning: Application to the Middle Rio Grande, *Aquat. Sci.*, *66*(4), 357–372.

Troch, P. A., T. Lahmers, A. Meira, R. Mukherjee, J. W. Pedersen, T. Roy, and R. Valdes-Pineda (2015), Catchment coevolution: A useful framework for improving predictions of hydrological change?, *Water Resour. Res.*, *51*, doi:10.1002/2015WR017032, in press.

Troy, T. J., M. K. V. Srinivasan, and S. Thompson (2015a), Moving sociohydrology forward: a synthesis across studies, Hydrol. *Earth Syst. Sci.*, *19*, 3667–3679, doi:10.5194/hess-19-3667-2015.

Troy, T. J., M. Pavao-Zuckerman, and T. P. Evans (2015b), Debates—Perspectives on socio-hydrology: Socio-hydrologic modeling: Tradeoffs, hypothesis testing, and validation, *Water Resour. Res.*, *51*, 4806–4814, doi:10.1002/2015WR017046.

Tucker, G. E., S. T. Lancaster, N. M. Gasparini, and R. L. Bras (2001), The channel-hillslope integrated landscape development model (CHILD), in *Landscape Erosion and Evolution Modeling*, edited by R. S. Harmon and W. W. Doe III, pp. 349–388, Kluwer Acad., Dordrecht.

Van Delden, H., P. Luja, and G. Engelen (2007), Integration of multi-scale dynamic spatial models of socio-economic and physical processes for river basin management, *Environ. Modell. Software*, *22*(2), 223–238.

van Emmerik, T., Z. Li, M. Sivapalan, J. Kandasamy, S. Pande, 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*, 4239–4259, doi:10.5194/hess-18–4239-2014.

Vennix, J. A. (1999), Group model-building: Tackling messy problems, *Syst. Dyn. Rev.*, *15*(4), 379–401.

Vergne, J. P., and R. Durand (2010), The missing link between the theory and empirics of path dependence: Conceptual clarification, testability issue, and methodological implications, *J. Manage. Stud.*, *47*(4), 736–759.

Viglione, A., G. Di Baldassarre, L. Brandimarte, L. Kuil, G. Carr, J. L. Salinas, A. Scolobig, and G. Blöschl (2014), Insights from socio-hydrology modelling on dealing with flood risk–roles of collective memory, risk-taking attitude and trust, *J. Hydrol.*, *518*, 71–82.

Vogel, R. M., U. Lall, X. Cai, B. Rajagopalan, P. K. Weiskel, R. P. Hooper and N. C. Matalas (2015), Hydrology: The interdisciplinary science of water, *Water Resour. Res.*, *51*, 4409–4430, doi:10.1002/2015WR017049.

Wagener, T., M. Sivapalan, P. A. Troch, B. L. McGlynn, C. J. Harman, H. V. Gupta, P. Kumar, P. S. C. Rao, N. B. Basu, and J. S. Wilson (2010), The future of hydrology: An evolving science for a changing world, *Water Resour. Res.*, *46*, W05301, doi:10.1029/2009WR008906.

Walker, L. R., D. A. Wardle, R. D. Bardgett, and B. D. Clarkson (2010), The use of chronosequences in studies of ecological succession and soil development, *J. Ecol.*, *98*(4), 725–736.

Walker, W. E., D. P. Loucks, and G. Carr (2015), Social responses to water management decisions, *Environ. Processes*, *2*, 485–509, doi:10.1007/s40710-015-0083-5.

Wardekker, J. A., A. de Jong, J. M. Knoop, and J. P. van der Sluijs (2010), Operationalising a resilience approach to adapting an urban delta to uncertain climate changes, *Technol. Forecast. Soc. Change*, *77*(6), 987–998, doi:10.1016/j.techfore.2009.11.005.

Warren, C., A. P. McGraw, and L. Van Boven (2011), Values and preferences: Defining preference construction, *WIREs Cognitive Sci.*, *2*(2), 193–205.

Wendebourg, J., and J. W. Harbaugh (1996), Sedimentary process simulation: A new approach for describing petrophysical properties in three dimensions for subsurface flow simulations, in *Geologic Modeling and Mapping*, edited by A. Förster and D. F. Merriam, pp. 1–25, Springer, N. Y.

Wescoat, J. L., Jr. (2013), Reconstructing the duty of water: A study of emergent norms in socio-hydrology, *Hydrol. Earth Syst. Sci.*, *17*, 4759–4768, doi:10.5194/hess-17–4759-2013.

Western, A. W., G. Blöschl, and R. B. Grayson (1998), How well do indicator variograms capture the spatial connectivity of soil moisture?, *Hydrol. Processes*, *12*, 1851–1868.

Western, A. W., R. B. Grayson, G. Blöschl, G. R. Willgoose, and T. A. McMahon (1999), Observed spatial organisation of soil moisture and its relation to terrain indices, *Water Resour. Res.*, *35*, 797–810.

Wheater, H. S., and P. Gober (2015), Water security and the science agenda, *Water Resour. Res.*, doi:10.1002/2015WR016892, in press.

Whipple, K. X., E. Kirby, and S. H. Brocklehurst (1999), Geomorphic limits to climate-induced increases in topographic relief, *Nature*, *401*(6748), 39–43.

Wild, T. B., and D. P. Loucks (2014), Managing flow, sediment, and hydropower regimes in the Sre Pok, Se San, and Se Kong Rivers of the Mekong basin, *Water Resour. Res.*, *50*, 5141–5157, doi:10.1002/2014WR015457.

Winder, N., B. S. McIntosh, and P. Jeffrey (2005), The origin, diagnostic attributes and practical application of co-evolutionary theory, *Ecol. Econ.*, *54*(4), 347–361.

Wood, E. F., et al. (2011), Hyper-resolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water, *Water Resour. Res.*, *47*, W05301, doi:10.1029/2010WR010090.

Wutich, A., A. C. White, D. D. White, K. L. Larson, A. Brewis, and C. Roberts (2014), Hard paths, soft paths or no paths? Cross-cultural perceptions of water solutions, *Hydrol. Earth Syst. Sci.*, *18*(1), 109–120.

Yaeger, M. A., M. Housh, X. Cai, and M. Sivapalan (2014), An integrated modeling framework for exploring flow regime and water quality changes with increasing biofuel crop production in the US Corn Belt, *Water Resour. Res.*, *50*, 9385–9404, doi:10.1002/2014WR015700.

Yevjevich, V. (1972), *Stochastic Processes in Hydrology*, 276 pp., Water Resour. Publ., Littleton, Colo.

Zehe, E., T. Blume, and G. Blöschl (2010), The principle of 'maximum energy dissipation': A novel thermodynamic perspective on rapid water flow in connected soil structures, *Philos. Trans. R. Soc. B*, *365*, 1377–1386.

Zeng, N., and J. D. Neelin (2000), The role of vegetation-climate interaction and inter-annual variability in shaping the African savanna, *J. Clim.*, *13*(15), 2665–2670.

Zhang, Z., F. Tian, and M. Sivapalan (2014), Groundwater dynamics under water saving irrigation and implications for sustainable water management in an oasis: Tarim River Basin, China, *Hydrol. Earth Syst. Sci.*, *18*, 3951–3967, doi:10.5194/hess-18–3951-2014.