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Key Points:

- Human activity is inherently a part of the natural hydrologic system
- Water, climate, energy, food, society, and environment are intertwined
- Models must account for bidirectional coupling of human/hydrologic systems

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Hydrology: The interdisciplinary science of water

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Abstract We live in a world where biophysical and social processes are tightly coupled. Hydrologic systems change in response to a variety of natural and human forces such as climate variability and change, water use and water infrastructure, and land cover change. In turn, changes in hydrologic systems impact socioeconomic, ecological, and climate systems at a number of scales, leading to a coevolution of these interlinked systems. The Harvard Water Program, Hydrosociology, Integrated Water Resources Management, Ecohydrology, Hydromorphology, and Sociohydrology were all introduced to provide different, interdisciplinary perspectives on water problems to address the contemporary dynamics of human interaction with the hydrosphere and the evolution of the Earth's hydrologic systems. Each of them addresses scientific, social, and engineering challenges related to how humans influence water systems and vice versa. There are now numerous examples in the literature of how holistic approaches can provide a structure and vision of the future of hydrology. We review selected examples, which taken together, describe the type of theoretical and applied integrated hydrologic analyses and associated curricular content required to address the societal issue of water resources sustainability. We describe a modern interdisciplinary science of hydrology needed to develop an in-depth understanding of the dynamics of the connectedness between human and natural systems and to determine effective solutions to resolve the complex water problems that the world faces today. Nearly, every theoretical hydrologic model introduced previously is in need of revision to accommodate how climate, land, vegetation, and socioeconomic factors interact, change, and evolve over time.

"Human activity is inherently part of the natural system"
Matalas et al. [1982]

1. Introduction

We live in exciting times. Not only are our planet and its water resources being transformed by both natural and anthropogenic influences but also the very field of hydrology is undergoing a similar transformation. Human impacts on the terrestrial hydrosphere are now so widespread that it is difficult to find a watershed or aquifer that does not reflect interaction among human and natural hydrologic processes [*Vörösmarty et al*., 2010, 2013]. We live in a world where biophysical and social processes are tightly coupled. Human impacts are now so pervasive that at least three of nine "planetary boundaries" associated with long-term sustainability have now been crossed, relating to climate change, biodiversity loss, and the nitrogen and phosphorus cycles [*Röckström et al*., 2009].

Correspondingly, a significant transformation in social and institutional systems is taking place. Our society is now global with ideas, goods, and services exchanged across the planet in a matter of days. Water is seen as a human right, and there is broad recognition of the need to address global water scarcity, to ensure safe drinking water and sanitation for the billions who do not have it [*U.N. General Assembly*, 2010], and of its role in food, energy production, maintaining ecosystem services, and hence in our collective ability to sustain the 9 billion people expected on the planet by 2050. The concept of virtual water or water embedded in agricultural and other products that are transported across watersheds and political boundaries is now established and may play a pivotal role in ameliorating global water scarcity [*Allan*, 1998] though not with potential long run limitations [*D'Odorico et al*., 2010].

There is some evidence of a departure from the traditional water resources planning model where a central planner at a watershed, regional, or a national scale focuses on the design and operation of water projects to balance social welfare, economics, and environmental concerns. Increasingly, and especially in places where water scarcity is the norm, and centralized water infrastructure systems are not able to meet emerging demands, the private or market-based development and commoditization of water resources has been increasing. Private water development and use may in many cases dominate the impact of centralized water infrastructure on hydrologic outcomes, particularly in regions experiencing significant groundwater depletion. Consequently, it is unclear whether the most significant human-induced hydrologic modifications are due to the impact of projects conceived by a central planner or the collective effect of many smaller developments due to private action. Many institutions have promoted participatory water management processes by stakeholders, and these in turn provide a challenge to hydrologists to develop novel, informative, and relevant products that can support decision making. A major issue in these deliberations is the potential effect of a mix of small and large scale water infrastructure on the overall system's performance, as well as on the resulting equity (spatial, economic as well as intergenerational), efficiency, and reliability across the potential set of users, including the environment.

While climate change has clearly emerged as a preoccupation for hydrologic engineers, planners, and scientists, efforts toward adaptation have highlighted the uncertainties that accompany traditional hydrologic analyses including questions as to the validity of hydrologic models under changing climate conditions. Planning for climate adaptation highlights the need to consider decisions from a variety of perspectives including: short and long-term system operation and infrastructure design; resource allocation and risk management strategies that integrate financial and structural solutions across multiple stakeholders and scales; and perhaps most importantly the emergence of global scale hydrology, across ocean, atmosphere, and land, so that watershed scale uncertainties as to precipitation and moisture fluxes can be better understood and reduced. Hydrologists are not alone, because oceanographers (who study the dynamics of 96% of water on the planet), atmospheric scientists, as well as social scientists emerge as accomplices who have a keen interest in fresh water hydrology and its impacts on human society. Collectively, we have begun to foster a One Water view of the world, as suggested in *Lall* [2014].

The One Water view is an evolution from a traditional to an active paradigm of hydrology [*Matalas et al*., 1982]. The traditional paradigm conceptually views the hydrologic cycle as centered on water quantity, such that water quantity can be assessed independently of water quality and that human activity is an external perturbation of the hydrologic cycle. In contrast, the active paradigm holds that human activity is inseparable from the natural system, that water quality is no less a concern than the quantity of water as it moves through the water cycle and that water quantity affects and in turn is affected by water quality. This shift from a traditional to an active paradigm is more of an evolution, with many new subfields having been advanced to account for the complex coupling between water quality and quantity and between human and hydrologic systems. In the following section, we provide what is perhaps the first brief historical review of our attempts to understand and manage coupled human/hydrologic systems. That historical review enables us to outline several challenges we face in our quest to understand and manage our evolving hydrosphere. The remainder of the paper outlines the fundamental advances concerning the coupling of humans and hydrologic systems, which may eventually enable us to sustainably manage our water resources.

2. A Historical Perspective on the Coupling of Human and Hydrologic Systems

The story of water and man is nearly as old as the story of human civilization. *Koutsoyiannis* [2014] reminds us that "Practical hydrological knowledge existed before the development of philosophy and science. This knowledge had its roots in human needs related to water storage, transfer and management." It is well known that access to water was critical for the establishment of many ancient civilizations in each of the major continents. Several civilizations vanished when faced with climate changes that disrupted their water supply or led to cataclysmic floods. *Wittfogel* [1957] introduced the idea of hydraulic empires or civilizations, whereby engineered control of hydrologic systems was central to the growth of agriculture and systems of taxation in ancient societies, as well as through European colonization. Though historians debate Wittfogel's ideas, the role water played in the evolution of the social structure and systems of centralized control in these societies is still central to their anthropological study. Many hydraulic innovations had significant local effects on hydrology. One could argue that current hydrologic conditions across the planet reflect the evolution of our control on water locally and regionally, on the modification of its atmospheric fluxes globally, and on the quality of the waters in ocean margins. Consequently, it is a bit surprising that the modern field of hydrology has been so wedded to trying to understand and model hydrologic systems as natural systems using the paradigms of Newtonian physics and classical statistics that typically do not consider the coupling between society and natural systems nor the possibility of nonstationarity or surprise.

Over the past few decades, there is an increasing awareness that hydrologic systems are changing in response to a variety of natural and human forces such as climate variability and change, water use and water engineering works (including dams, levees, diversions, storm water systems, and groundwater pumping), and land cover change (including deforestation, urbanization and agriculture). Over 30 years ago, *Matalas et al*. [1982] articulated the need for the integration of human and hydrologic systems when they said that "it must be recognized that human activity is inseparable from these (hydrologic) concerns, both influencing and affected by them, both intentionally and inadvertently." In contrast to the "traditional paradigm" which holds the human enterprise as a thing apart from hydrologic systems, *Matalas et al*. [1982] introduced an "active paradigm" which "*recognizes that human activity is inherently part of the natural system*."

Over the years, there have been many initiatives within our field to address the complex interactions between society and water systems. Though other efforts came earlier, one of the first advances in this area was this very journal. From its inception in 1964, *Water Resources Research* is an interdisciplinary journal which "publishes original research in the natural and social sciences of water" and "emphasizes the role of physical, chemical, biological, and ecological processes in water resources research and management, including social, policy, and public health implications." Only a few years earlier, the book "*Muddy Waters*" [*Maass*, 1951], a critique of the policies of the U.S. Army Corps of Engineers, led to a complete revaluation of their practices and the inclusion of social scientists into the planning process for water infrastructure. Perhaps, even more seminal was the collaborative educational and research effort known as the Harvard Water Program which began in 1955 under the direction of a political scientist and government planner, Arthur Maass [see *Reuss*, 2003]. The Harvard Water Program brought together engineers, hydrologists, economists, government planners, and other social scientists to improve our ability to integrate societal concerns into the water resources planning and management process, typically from a central planner perspective. This led to the seminal treatise by *Maass et al*. [1962] titled "*Design of water-resource systems: New techniques for relating economic objectives, engineering analysis, and governmental planning*." The ideas born with the Harvard Water Program and *Maass et al*. [1962] have evolved considerably over the decades leading to the discipline of water resource systems nicely summarized by *Loucks et al*. [1981] and *Loucks and van Beek* [2005] and several other comparable texts. Note that the discipline of water resource management was historically developed as an interdisciplinary area that embraces societal concerns based on hydrology, economics, and engineering, with even broader consideration of political, religious, and ethical concerns [*Gleick*, 1999; *Armstrong*, 2006; *Chamberlain*, 2008].

The next seminal effort to introduce a systematic scientific approach to understanding the interactions, coupling, and feedback mechanisms which exist between society and natural water systems was described in the paper titled "*Water and mankind – a complex system of mutual interaction*" by *Falkenmark* [1977]. At that time, *Widstrand* [1978] argued that due to the complex coupling between society and water resource systems, there is a need for a greater connection between the social sciences and water resource planning. *Falkenmark* [1979] was perhaps the first to argue for the need for a new subfield of hydrology to "provide improved analysis of social consequences of water projects," which she termed "hydrosociology." She warned that "cultural, religious and social differences between regions will pose enormous challenges to the transfer of knowledge and technology from one cultural and climatic region to another" [*Falkenmark*, 1979]. *Delli Priscoli* [1980] was perhaps the first journal editor to advance a "call for papers" on the subject of water and people.

The next major initiative to combine societal concerns into water planning and management solidified after the Dublin Principles were introduced in 1992 which led to the field of Integrated Water Resources Management (IWRM). IWRM is now internationally a widely accepted process which promotes the coordinated development and management of water, land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems [*Global Water Partnership*, 2000]. *Kadi* [2014] provides an exhaustive review of the international history of IWRM and *Kirshen et al*. [2004] provide an example of an interdisciplinary educational program in IWRM.

It was not until the 21st century, nearly 30 years after *Falkenmark's* [1977, 1979] early call for action, that the hydrologic challenges arising from human-induced hydrologic change led to another call for action to redefine the science of hydrology [*Wagener et al*., 2010]. Their call was quite effective because several new subfields of hydrology were subsequently advanced to account for interactions between society and hydrology including the fields of hydromorphology [*Vogel*, 2011], sociohydrology [*Sivapalan et al*., 2012], water diplomacy [*Islam and Susskind*, 2013] as well as the Panta Rhei initiative advanced by [*Montanari et al*., 2013]. The most recent *National Research Council* [2012] report "*Challenges and Opportunities in the Hydrologic Sciences*" concludes that "furthering understanding of the processes that link components of the water cycle is no less important than understanding the human impacts on the water cycle." *Vogel* [2011] used an analogy to the subfield of geology known as geomorphology to advance both the engineering and scientific field of hydromorphology as a subfield of Hydrology which deals with the structure and dynamic evolution of the earth's water resources. Analogous to geomorphology which deals with the dynamic morphology of the earth system, hydromorphology addresses the dynamic morphology of the hydrosphere and its component water resource systems, due to both natural and anthropogenic influences. Similarly, *Sivapalan et al*. [2012] advanced the new subfield of hydrology known as sociohydrology, the science of people and water, a new science aimed at improving our understanding of the dynamics and coevolution of coupled human water systems. To assure scientific progress in these new initiatives, *Montanari et al*. [2013] organized the "Panta Rhei" ("everything flows") decadal research effort under the auspices of the International Association of Hydrological Sciences (IAHS). *Montanari et al* [2013] define the overall goal of Panta Rhei to reach an improved interpretation of the processes governing the water cycle by focusing on their changing dynamics in connection with rapidly changing human systems. They further define a more practical goal to improve our capability to make predictions of water resources dynamics to support sustainable societal development in a changing environment. In the short time since its inception, the field of sociohydrology has already inspired considerable attention. For example, in a recent special issue of the *Journal of Hydrology*, titled "*Creating Partnerships Between Hydrology and Social Science: A Priority for Progress*," *Reddy and Syme* [2014] argue that "If hydrology is to continue to have a beneficial impact on the water resource and the community it needs to seek to place itself in partnership with social scientists." Surely, there is much to be learned from the early efforts to integrate hydrology with the social sciences introduced by the Harvard Water Program.

It is relevant to question the need for so many new and related subdisciplines of hydrology because as *Sivakumar* [2012] argued, there is considerable overlap among some of the initiatives. In effect, they speak to the broad recognition from different corners that the study of water and humans are inexorably intertwined. For example, it is becoming increasingly difficult to study energy, food, health, or the environment without some expertise in water. The same may be said of the study of climate, water, and humans, which until the most recent discussion about anthropogenic climate warming was really a story about how climate and society came together through their water interface. Indeed, climate variability seen through the lens of water emerges as a determinant of the potential per capita wealth of nations as illustrated by [*Brown and Lall*, 2006]. As with other earth sciences, hydrology is best placed in the human context as a resource, an environment, and as a medium for natural and anthropogenic hazards. These three aspects of hydrology encompass its application and also motivate the understanding of its bi-directional linkage to society. Consequently, we embrace uniformly the different initiatives that highlight the synergy between water, humans, and climate, as well as between the scientific and engineering aspects of hydrology [see *Koutsoyiannis*, 2014] and advance the following three propositions within which we describe our reflections and proposed ideas for the future of hydrology and water resources management:

1. Adequate understanding of hydrologic systems for water resources management requires consideration of the coupled human/ hydrologic system.
2. Integration of human systems into hydrologic design challenges the emphasis on physical processes as the main predictor of hydrologic response.

3. Knowledge discovery through "big data" shows promise for understanding the coupled human/hydrologic system.

In elaborating these propositions, we outline some of the challenges we face in our quest to understand and manage our evolving hydrosphere. We outline the fundamental advances which will be needed in the areas of availability and management of data, advanced modeling methods, uncertainty analysis, and the type of fundamental conceptual developments which will be needed to develop and test new hypotheses concerning the coupling of humans and hydrologic systems to enable us to sustainably manage our water resources.

3. Proposition 1: Adequate Understanding of Hydrologic Systems for Water Resources Management Requires Consideration of the Coupled Human/Hydrologic System

Examples of coupled human and hydrologic systems and their impacts are now pervasive. To highlight the human-hydrology coupling, we provide three examples of recent research which has documented the direct and indirect effects associated with the coupling and associated feedbacks which exist between human and hydrologic systems. These effects determine the coevolution of these systems over the centuries, and the recent acceleration of this coevolution during what is being called the Anthropocene epoch (The term "Anthropocene" is not formally recognized by the U.S. Geological Survey as a unit of geologic time. We use it here informally. See *Zalasiewicz et al*. [2011] for a discussion of the origins of the term.)

A simple yet rigorous approach for quantifying direct human-hydrologic interactions is to construct and analyze the water budgets for hydrologic systems (stream basins or aquifers) that explicitly include human withdrawals (H_{out}) and return flows (H_{in}) as terms in the governing water-balance equation (Table 1). The character and intensity of direct human-hydrologic interaction in each case (the "water-use regime") may then be defined by quantifying the magnitudes of the human fluxes relative to each other and relative to total fluxes through a given system [*Weiskel et al*., 2007]. Below, we use this approach to characterize three regional systems that have been strongly impacted by human water-use practices.

3.1. Yellow River (Huang He) Basin, China

The Yellow River Basin (YRB) is one of the world's most intensively developed large hydrologic systems. The climate is relatively dry, with precipitation (P), evapotranspiration (ET), and runoff (P – ET) averaging about

Table 1. Annual Water Budgets of Selected Watersheds and Aquifers[a]

		Net Inflows, mm/yr			Net Outflows, mm/yr							
Stream Basin[b]	Area	P - ET	H_{in}	Sum of Net Inflows	SW_{out}	H_{out}	Sum of Net Outflows	Net dS/dt	P	ET	h_{out}	h_{in}
	km^2	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr		
Yellow R., 1998–2000	742,000	72	11	83	9.2	67	76	6.9	484	413	0.88	0.15
Aquifers[c]	Area	R_T	H_{in}	Sum of Net Inflows	D_T	H_{out}	Sum of Net Outflows		P	ET	h_{out}	h_{in}
	km^2	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr		mm/yr	mm/yr		
E. Snake R. Plain, 1980	28,000	142	213	355	312	50	362	−7.4	–	–	0.14	0.59
CA Cent. Val., 1961–1977	51,800	48	223	271	7.1	283	290	−19	–	–	0.98	0.77
Cape Cod, 2003	880	670	35	705	663	39	702	0	–	–	0.06	0.05

[a]All water budgets obtained from *Weiskel et al*. [2007], reexpressed in mm/yr. Source data: Yellow River Basin, *Cai and Rosegrant* [2004]; Eastern Snake River Plain and CA Central Valley Aquifers, *Johnston* [1999]; Cape Cod Aquifer, *Walter et al*. [2004].

[b]Governing stream basin water-balance equation: (P – ET) + H_{in} – dS/dt = SW_{out} + H_{out} = NetFlux$_{basin}$, where P = precipitation; ET = evapotranspiration; H_{in} = human return flows + imports to basin; dS/dt = change in basin storage (positive, negative, or zero); SW_{out} = surface water outflows; and H_{out} = human withdrawals for local use or export from basin, all in units of mm/yr.

[c]Aquifer water-balance equation: R_T + H_{in} – dS/dt = D_T + H_{out} = NetFlux$_{aquifer}$, where R_T = total recharge to the aquifer from precipitation, surface waters, and adjacent aquifers; D_T = total discharge from the aquifer to surface waters, adjacent aquifers, and to evapotranspiration; H_{in} and H_{out} = return flows + imports directly to, and withdrawals directly from, the aquifer, all in mm/yr.

480, 410, and 70 mm/yr, respectively (Table 1). Water resources in the basin are developed for irrigation, urban, and industrial use. From 1950 to 2000, irrigated area in the basin increased over ninefold from 0.8 million to 7.5 million hectares [*Cai and Rosegrant*, 2004]. Human withdrawals (H_{out}) from the basin during 1998–2000 averaged 67 mm/yr (Table 1) about six times larger than return flows (H_{in}; 11 mm/yr). H_{out} comprised 88% of net outflow from the basin, with stream outflow (SW_{out}) making up the rest. The result, averaged over the basin, is a highly depleted water-use regime (Figure 1; lower right quadrant). Such regimes can seriously degrade aquatic ecosystems [*Poff et al.*, 2010] by reducing or eliminating streamflows on a seasonal or average-annual basis—conditions commonly observed in the YRB [*Cai and Rosegrant*, 2004].

3.2. Eastern Snake River Plain Aquifer, Idaho

In direct contrast to the depleted regime of the Yellow River Basin, the Eastern Snake River Plain (ESRP) Aquifer exemplifies a surcharged water-use regime (large human inflows relative to overall inflows to the hydrologic system; Figure 1, upper left quadrant). Withdrawals (H_{out}) from the aquifer averaged 50 mm/yr in the study period, comparable to the 67 mm/yr withdrawn from the YRB [*Garabedian*, 1992]. However, irrigation return flows to the aquifer, from groundwater and imported surface water sources, totaled 213 mm/yr, nearly 20 times larger than return flows to the YRB (11 mm/yr). In some surcharged aquifers in arid regions, imported irrigation water causes the water table to rise substantially. This can result in soil water-logging, as well as soil salinization from groundwater evapotranspiration [*Schoups et al.*, 2005]. However, the high permeability of the ESRP volcanic aquifer appears to have dampened water table rise in the Snake River Plain. Instead, the surcharged regime has led to large increases in groundwater discharge from springs along the Snake River, relative to predevelopment discharge rates.

3.3. California Central Valley Aquifer

The California Central Valley (CCV) is among the most productive agricultural regions in the world. This productivity is enabled by high rates of irrigation, derived from surface water imports from the adjacent Sierra Nevada and groundwater withdrawals from the underlying regional aquifer [*Johnston*, 1999; *Faunt*, 2009]. By focusing initially on the water budget of the underlying CCV aquifer (Table 1, Figure 1), we observe that H_{out} and H_{in} are by far the dominant fluxes in the aquifer water budget, totaling 283 mm/yr and 223 mm/yr, respectively, or 98% and 77% of net aquifer fluxes during the study period. The regime is located in the upper-right quadrant of the regime space (Figure 1), between the human-flow dominated (churned) and depleted end-members. Negative impacts of this mixed regime include groundwater quality degradation from the recycling of irrigation return flows [*Burow et al.*, 2013], as well as depletion of aquifer storage and associated land subsidence from aquifer compaction [*Faunt*, 2009; *Famiglietti et al.*, 2011]. Table 1 and Figure 1 also include the Cape Cod Aquifer for comparison—a system where the natural recharge rate (670 mm/yr) is 14 times larger and the human fluxes are 86% smaller than those of the CCV Aquifer (per unit area), resulting in a natural-flow-dominated regime.

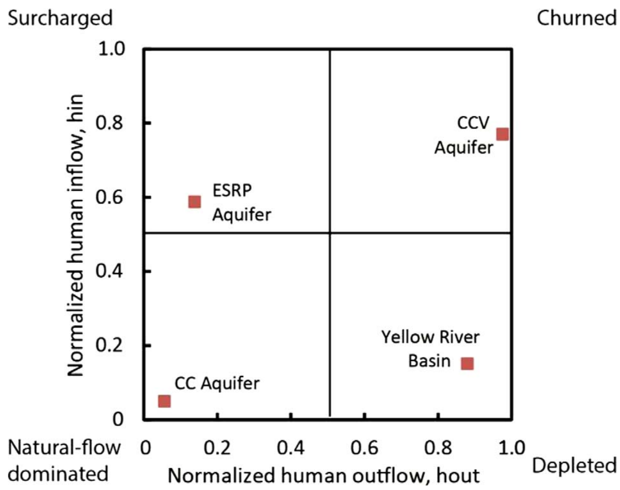

Figure 1. Annual water-use regimes of the Yellow River Basin, and the Eastern Snake River Plain (ESRP), California Central Valley (CCV), and Cape Cod (CC) Aquifers. Normalized human outflow, $h_{out} = H_{out}$/NetFlux. Normalized human inflow, $h_{in} = H_{in}$/NetFlux, where NetFlux = the sum of human + natural outflows from the hydrologic system (stream basin or aquifer). See Table 1 for water budgets of each hydrologic system, and definition of NetFlux. Four end-member regimes are shown at the corners of the plot.

Lo and Famiglietti [2013] have presented a fully coupled modeling analysis of the California Central Valley (CCV) system that allows for the complete interaction between humans, hydrology and climate. Their approach and major results are summarized below.

First, a land-surface model [*Oleson et al.*, 2008] is used to simulate ET fluxes from the full array of land cover types in the CCV under two scenarios: (1) with cropland irrigation and (2) without irrigation (the control scenario). Second, the vertical vapor fluxes associated with the two scenarios are separately incorporated into two runs of a global circulation model (GCM) [*Gent et al*., 2010]. The differences (anomalies) between the irrigation and control GCM runs, with respect to horizontal vapor flux and precipitation are then analyzed across a broad geographic area (from California to the U.S. Atlantic coast).

These modeling experiments result in several remarkable findings. First, irrigation leads to a 100% increase in ET during the growing season in the CCV, relative to the no-irrigation case. Second, the water vapor generated by this extra ET does not significantly affect local precipitation during the growing season. Rather, it is transported eastward to the Rocky Mountain headwaters of the Colorado River Basin, where it cools, condenses, and causes an increase in summer precipitation and streamflow. Some of this increased streamflow is diverted to southern California (though not to the CCV) via the Colorado River Aqueduct and All-American Canal. Interestingly, similar regional cycling and transport of moisture from agriculture have been reported in *Kustu et al*. [2011]. In short, the study shows that intensive irrigation practices in semiarid-to-arid regions like the CCV can affect climate, hydrology, and water supply at subcontinental scales (10^5-10^6 km^2), creating, in some cases, previously unsuspected "anthropogenic loops" in the hydrologic cycle.

This study and others like it [e.g., *van der Ent et al*., 2010; *Puma and Cook*, 2010; *Cook et al*., 2014] help to broaden our understanding of human-hydrologic interactions in several ways. First, they show that human water-use practices affect not only the internal water storage and boundary fluxes of hydrologic systems (stream basins and aquifers); human water-use practices can also feedback upon the climatic boundary conditions of those systems, both locally and over long distances. Second, the study adds to a growing literature [e.g., *Siebert et al*., 2010] asserting the primary importance of irrigation in human-hydrologic interaction. Not only does irrigation represent 70% of all human water withdrawals and 90% of consumptive water use globally [*Siebert et al*., 2010], irrigation is also most prevalent in arid and semiarid regions where its relative impact on hydrology, aquifer storage, and climate are likely to be greatest [e.g., *Castle et al*., 2014]. Third, studies like those of *Lo and Famiglietti* [2013] demonstrate that land-surface and global circulation models can be useful tools for examining coupling among human and natural hydrologic systems. Finally, such studies help to correct the historic "blue-water bias" in hydrologic assessment by fully addressing both blue (groundwater and surface water) and green (*P* and ET) aspects of human interaction with the water cycle [*Falkenmark and Rockström*, 2006, 2010; *Weiskel et al*., 2014].

3.4. Reflections—Integrating Climate and Economics With Hydrology

With these examples, we see that at least regionally, there are significant and measurable effects of human activity on terrestrial and atmospheric hydrology, and that integrated water-balance modeling of the structural responses of the hydrologic system may be used to quantify these impacts, using remote sensed and directly measured data together with inference on model parameters. However, these examples do not explore why the specific human influence on hydrology evolved in the first place (i.e., they only describe one direction of the human-hydrologic coupling). This is not surprising since the traditional hydrologic modeling paradigm is focused on a river basin (or aquifer) as a boundary value problem, with human activity and climate as exogenous to the system. In this context, even a dynamic water-balance model is still seen as a quasi-equilibrium model responding to slowly changing boundary conditions, and the interest is in identifying the structural response of hydrologic attributes to these changes in system boundaries over an averaging interval. For instance, in the *Lo and Famiglietti* [2013] example, the interest was in understanding how the atmospheric and terrestrial hydrologic balance may change with or without irrigation over the specified area (i.e., in the structural response to those boundary conditions). How the boundary conditions of the system may change in response to the emerging hydrologic conditions and other factors is not part of the dynamics.

Human modification of the hydrologic cycle depends on the socioeconomic factors that define the use of water, as well as the efforts to regulate both the flow and the quality of water. As we consider the pace of change in the Anthropocene, it is necessary for us to consider the long-term (i.e., decade or longer) evolution of the hydrologic system, in which case, one needs to build a conceptual model of how these coupled human-hydroclimatic dynamics may emerge. The Western United States has seen significant droughts since the 1990s and *Seager and Hoerling* [2014] argue that this may be the normal condition under a warmer planet. The region is marked by vast open spaces, irrigated agriculture, significant hydropower generation, and a series of large urban centers. Trans-basin diversions and large multipurpose reservoirs were developed in the twentieth century, as part of a federal mandate to settle the Western United States. Water allocation principles were developed for the Colorado and other rivers, and a prior appropriation water rights doctrine was developed in the 19th century to address upstream-downstream conflicts between water users. Prior appropriation gives senior water rights up to a fixed amount per season or year to a user for their designated beneficial use (agriculture, urban use, mining, etc.). These rights can be traded or mortgaged, like other property rights, but the user can lose the rights if they fail to demonstrate the beneficial use of water for their designated purpose. In a drought situation, the junior water right holder may not be able to obtain water, and hence such rights will have lower economic value, and their ultimate use may reflect its associated risk and value. Thus, from a human-hydrologic interaction perspective, the "model" would need to recognize this legal structure and translate it into a potential reduction in irrigation during droughts, as would emerge from the water rights structure. However, this scenario may not really emerge if the irrigation shifts to groundwater use, which is more expensive to develop and operate, but would emerge during a drought event, or if all the surface water rights are subscribed to, and groundwater is not regulated.

In the last 25 years, a potentially significant change in the institutional dynamics of water allocation and use has been emerging in the West. First, in some regions, short and long-term trades of water rights have been increasing, and many analysts have called for an active, regulated market, following the Australian example in the Murray-Darling basin. Some of the longer term trades are driven by urbanization, followed by the transfer of agricultural water rights associated with the landowner to urban or energy or environmental sectors, i.e., they are driven by regional economic and demographic trends. However, other trades are a direct response to the hydroclimatic situation and are quite dynamic. The presence of reservoirs and water rights associated with them has led to the introduction of water markets based on drought water banks and groundwater banking [see *Loomis*, 1992; *Israel and Lund*, 1995; *Howitt and Hanak*, 2005]. Such strategies have facilitated the transfer of water rights from users who are less likely to derive economic benefit (e.g., farmers growing alfalfa or other low cash value crops) to those who are willing to pay more than the original owner is likely to derive from their own activity (e.g., farmers with high cash value crops, ecological interests, energy producers, mining, and cities). Such water transfers could lead to significant changes in the regional water balance because changes in the source (e.g., surface water to groundwater or desalination) may lead to changes in evapotranspiration as crop area is reduced, or changes in water quality as water use and return flows shift from agriculture to mining or urban centers, or as investments are made in water conservation and reuse. If one does not think about the coevolution of climate, society, and hydrology, these factors may seem to be of secondary importance—they emerge as perturbations in random dry or wet years, or as gradual trends that can be exogenously specified.

From the analysis of paleoclimatic (tree ring) reconstructions [e.g., *Woodhouse et al.*, 2006; *Meko et al.*, 2007] of Colorado River hydrology, one notes nonstationary variations at interannual and multidecadal time scales driven by El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO) [*Nowak et al.*, 2012]. The hydrology of this large region responds to a combination of these factors, such that the long epochal periods with either a negative or a positive water anomaly may be punctuated by decade long periods that either amplify or dampen the century scale variation. Since the spatial signatures of these climate modes vary, the combined effect can appear quite heterogeneous. However, as the available water sources in a region are nearly fully appropriated, persistent climate regimes can enable the development of institutional response strategies that can then lead to a new water use structure that the social and physical system evolves to, in turn systematically changing the hydrologic outcomes in the basin. Certainly, projected anthropogenic climate change may also induce such transitions. However, none of the current generation of climate models reproduces the long-term statistics of regional precipitation and hydroclimate that are expressed in the paleo and historical record, hence we can only speculate how those climate models will change in the future. The climate change projections exhibit much less persistence and organization than is expressed in the historical record, and despite the uncertainty in those projections, the amplitude of projected hydrologic change due to anthropogenic factors over the next 50 years or so is not greater than that noted in the organized and persistent climate modes over the last 700 years. Consequently, a rigorous analysis of hydrologic futures in such a region over the next 50 years would require a conceptual model of the evolution of water markets, regulatory structures, and technologies which may evolve in response to protracted regional drought or protracted wet periods. This requires a spatiotemporal understanding of the climate modes, their impact on hydrologic regimes, and scenario development as to the potential emergent behaviors. In the absence of such an integrated approach, we may view emergent shocks to the water systems as Black Swan events [*Taleb*, 2010] which are unexpected events, which are potentially catastrophic, yet have a very low probability of occurrence and are usually accompanied by the emotion of surprise [*Fiering and Kindler*, 1987]. Such events may be described by a stationary probability distribution, residing far out on the tail of the distribution, with an average return period that may exceed several lifetimes, such as the probable maximum flood. See our later section on "true uncertainty," in which we draw a distinction between Black Swan events which may be evaluated with thick tailed probability distributions and other events governed by "true uncertainty," for which there is "no scientific basis on which to form any calculable probability whatever." [*Keynes*, 1937, p. 217]. In such an environment, addressing the occurrence of Black Swans suggests seeking a nonprobabilistic basis for making water management decisions.

4. Proposition 2: Integration of Human Systems Into Hydrologic Design Challenges the Emphasis on Physical Processes as the Main Predictor of Hydrologic Response

Every few decades, a new handbook of hydrology has been published [*Chow*, 1964; *Maidment*, 1993] (V. P. Singh, Handbook of Applied Hydrology, McGraw-Hill, New York, in preparation, 2015) summarizing the state of our knowledge concerning both hydrologic science and engineering. We contend that nearly every aspect of such hydrology handbooks, textbooks, and monographs have largely ignored the human component of the hydrologic systems and thus are in need of revision to include the impacts of humans. We also contend that some initial progress has been made along these lines which we summarize.

Correspondingly, there has been surprisingly limited advance on understanding the role of water in the social sciences. Water law, water economics, water policy, water diplomacy, water management, and water and development have not emerged in the same way that the corresponding study of climate and society, or energy and society, or food systems and their relationship to poverty and development has emerged as academic lines of inquiry. Yet, water as a resource presents dilemmas typical of common pool resources and its allocation has significant short-term and long-term societal implications. When water is viewed as a resource, its interaction with society in terms of flows in rivers, and the quality of water bodies has emerged as a significant regulatory and water management issue, with considerable potential for differential social and ecological impacts. The considerable hydrologic study of natural hazards such as floods and droughts and the mitigation of the risks posed by them has been driven in part by legislative or policy measures, and yet there has been a limited analysis of how floods and droughts have led to subsequent hydrologic change, or to societal resilience in the face of repeated exposure, institutional response, and event recovery.

This section reviews some initial progress along these lines some of which, presumably, will be integrated into future textbooks, handbooks, and monographs. We review the recent progress into the integration of the human footprint into three areas: (1) hydrologic processes, (2) hydrologic design, and (3) decision-oriented water resource models.

4.1. Integration of the Human Footprint Into Hydrological Processes

Many of theoretical and empirical models for hydrologic processes were developed for, and tested with, natural watersheds and as a result, they cannot describe hydrologic processes altered by human interferences. In fact, these models cannot even simulate the physical processes under stationary conditions due, in part, to the confounding impacts of our ignorance of human and physical systems being mapped on the model parameters [*Hejazi et al*., 2008]. In this section, we review a few recent advances which have adapted traditional models for hydrologic processes in natural watersheds to accommodate human influences.

4.1.1. Baseflow and Groundwater Outflow

The baseflow response of a watershed is a fundamental hydrologic process with a rich literature relating to both its engineering and scientific aspects. Hydrograph recessions have long been modeled under the assumption that the watershed behaves like a linear reservoir, which leads to a log linear baseflow recession. Ever since *Brutsaert and Nieber* [1977] introduced the theoretical basis for baseflow recessions, there still remains considerable controversy over the issue of whether or not watersheds behave as linear or nonlinear reservoirs in the context of their baseflow response [e.g., *Biswala and Kumara*, 2014]. *Brutsaert and Nieber* [1977] provide a theoretical basis for, and subsequent validation of, the linear reservoir hypothesis on numerous natural watersheds. However, *Wang and Cai* [2009] showed that the log linear relationship (linear reservoir hypothesis) does not hold when human-induced flow (e.g., return flow from an irrigation system or effluent discharge from an urban area) accounts for a major fraction of gross streamflow. Thus, it is entirely possible that a good deal of the “scientific” debates over the past few decades concerning whether or not watersheds behave like linear reservoirs, or not, under baseflow conditions have been confused by the impact of human water withdrawals and return flows.

Wang and Cai [2009] and *Thomas et al*. [2013] provide theoretical expressions for modeling hydrograph recessions under human influence. Interestingly, *Thomas et al*. [2013] document that even very small human water withdrawals can have very large impacts on our ability to model baseflow recessions. Despite the continuing controversy over whether or not the baseflow response is linear or nonlinear [e.g., *Biswala and Kumara*, 2014], estimation of the baseflow recession constant continues to be required for many hydrologic models, too numerous to list exhaustively (e.g., HEC-HMS, HSPF, SWAT). *Thomas et al*. [2013] describe new procedures for the estimation of the baseflow recession constant under human influence.

4.1.2. Evapotranspiration

Land development and other human activities can have important impacts on evapotranspiration (ET) processes. *Cheng et al*. [2011] used continental scale satellite-based ET data sets to document a strong linear relationship between PET/P (annual potential ET to annual precipitation) and ET/P on an interannual basis. They found that interannual variability in ET defined within the Budyko curve framework can be captured by a linear function, with a high average goodness of fit over 500 catchments in the continental United States. In addition to the usual energy and water limitations on ET, their results indicate that the three forces of (1) soil water storage, (2) sensitivity of vegetation to climate variability, and (3) human interferences, together, govern the interannual variability of ET. They document how human activities such as agricultural land development and irrigation can impact the Budyko relationship. Importantly, the nonlinear relationship characterized by the Budyko curve that was reported in many previous studies is, apparently, inadequate to describe the interannual ET variability when human interferences are present [*Zeng and Cai*, 2015].

4.2. Integration of the Human Footprint Into Hydrologic Design

Most previous hydrology research relating to hydrologic design assumes both a stationary past and future, in spite of the fact that almost 40 years ago, *Matalas and Fiering* [1977] introduced a generalized statistical decision-oriented approach for handling the increased uncertainty due to climate change using the concepts of robustness, redundancy, resilience, and regret. The now nearly pervasive awareness of potential nonstationarity led *Vogel* [2011] to suggest that nearly every hydrologic method upon which our profession is based will need to be adapted to account for the increased uncertainty and nonstationarity that have become central challenges, due in part to our lack of understanding of the interaction between humans and hydrology. The notion that “stationary is dead” is now pervasive as indicated by over 1000 citations, to date, of *Milly et al*. [2008]. Perhaps, we should not be so quick to dispense with the notion of stationarity given that to date, most of our water infrastructure was designed under the assumption of stationary conditions, yet there have been ‘‘very few failures of the nation’s water management infrastructure—i.e., where the infrastructure failed before its design capacity was exceeded’’ [*Stakhiv*, 2011]. *Matalas* [2012] provides ample reasons for questioning “the degree to which real or perceived nonstationarities in hydrologic processes (should) affect the underlying processes and methods of making water planning and management decisions.” He argues that “the assumption of stationarity has not yet been pushed to the limit of its operational usefulness in the face of a changing climate.” *Matalas* [2012] introduces a compelling analogy to “an earlier generation of hydrologists and water managers in coming to grip with persistence, short- and long-term memory, in resolving an old issue referred to as the Hurst phenomenon, an issue as perplexing then as nonstationarity is now.” Here we outline a few advances for hydrologic planning under nonstationary conditions by adapting traditional risk-based approaches which have served us well under stationary conditions.

4.2.1. Hydrologic Design Under Nonstationary Conditions

On the one hand, there is a critical need to adapt the traditional approaches for hydrologic design to account for nonstationarity in hydrologic processes, particularly in rapidly growing urban areas where the frequency and magnitude of floods have, and may continue, to increase. Continental scale studies in both the United States [*Vogel et al*., 2011] and Africa [*Di Baldassare et al*., 2010] now agree that considerable changes in the frequency and magnitude of floods have occurred in regions which have undergone intensive human settlement (e.g., urbanization). Surely, such significant historical changes should lead hydrologists, at the very least, to update design floods to current conditions. Importantly, such changes in flood hazard are due to changes in both the geomorphological characteristics of rivers, as well as changes in both the frequency and magnitude of river discharge [*Slater et al*., 2015]. Considering the now pervasive awareness of hydrologic nonstationarity, we are surprised at how little attention has been given to the development of methods for accounting for nonstationarity in hydrologic design. Foremost among these issues relates to our ability to estimate the frequency of future hydrologic events of interest.

Traditional probabilistic approaches for defining risk, reliability, and return periods under stationary hydrologic conditions assume that extreme events arise from serially independent time series with a probability distribution whose moments and parameters are fixed. In a stationary world, the occurrence of independent annual hydrologic events with exceedance probability equal to p follows a geometric distribution so that the mean return period is always equal to $1/p$. This fundamental assumption forms the basis of most existing hydrologic design methods. *Olsen et al*. [1998], *Salas and Obeysekera* [2014], and others cited therein introduce expressions for computing the risk and the average return period when the exceedance probability p is no longer constant from 1 year to the next. L. Read and R. M. Vogel (Risk, reliability, and return periods under nonstationarity, submitted to *Water Resource Research*, 2015) document that under nonstationary conditions the shape of the distribution of the time to the next hydrologic event depends critically upon the planning horizon, the degree of nonstationarity, and the variability of the hydrologic event of interest. Thus, planning under nonstationary conditions is fundamentally different than under stationary conditions, where the shape of the distribution of the return period is invariant, always following an exponential (continuous) or geometric (discrete) distribution.

Matalas and Fiering [1977] and *Rosner et al*. [2014] introduced a generalized risk-based approach to hydrologic design under nonstationary conditions which integrates the uncertainty associated with future nonstationarity into the decision process. *Matalas and Fiering* [1977] introduced the notions of redundancy, resilience, robustness and regret into our parlance, and provide an example of their use in hydrologic design within the context of climate change. *Rosner et al*. [2014] show how the likelihood of underdesign and overdesign can be computed from trend hypothesis test results and combined with an adaptation strategy infrastructure costs and damages avoided to provide a rational decision approach under nonstationary conditions. *Rosner et al*. [2014] demonstrate how the criterion of expected regret can integrate the statistical, economic, and hydrological aspects of a hydrologic design problem in a nonstationary world.

4.2.2. Empirical Human/Hydrologic Models

Recent advances in data mining now enable discovery and development of new hydrologic models by explicitly accounting for both hydrologic and human variables. Numerous empirical multivariate relationships have been developed which characterize the impact of various anthropogenic influences on streamflow regimes ranging from flood regimes [*FitzHugh and Vogel*, 2011] and low-flow regimes [*Homa et al*., 2013; *Schnier and Cai*, 2014] to the entire flow regime [*McManamay*, 2014]. Importantly, the accuracy of the regional models of low-flow statistics introduced by *Homa et al*. [2013] are shown to yield considerable improvements over previous regional models, largely due to the careful inclusion of a wide range of anthropogenic influences. *Homa et al*. [2013] document that dam storage, water withdrawals and discharges, and nonpoint source land use modifications such as impervious cover all have considerable impacts on low streamflows.

5. Integration of the Human Footprint Into Decision-Oriented Water Resource Models

Ever since the early contributions of the Harvard Water Program [*Maass et al*., 1962] and the now fertile field of water resource systems planning [*Loucks et al*., 1981; *Loucks and van Beek*, 2005], numerous efforts have been made to integrate the economic and social assessment of human decision-making processes with hydrological processes. Such water resource systems modeling approaches are intended for use in support of water resources design, planning and management without much attention to the coupling between the human and natural components.

Recently, researchers from the Coupled Natural and Human Systems (CNHS) community have attempted to integrate human and natural systems dynamics in a consistent complex system so that the interactions and feedbacks between the two components can be modeled endogenously and the system level hydrological patterns and human behavior (i.e., system emergence) can be captured [*Liu et al*., 2007]. The hydrology community has developed many spatially distributed hydrologic models focusing on the heterogeneity of biophysical parameters and processes. However, when such models are applied to addressing water resources planning and management problems, the human dimension is usually inserted in a "lumped" form, assuming centralized institutions and ignoring the heterogeneity of water users and/or stakeholders' behaviors. Thus, the primary and perhaps most formidable challenge involves a quantitative description of the behavior of individuals (e.g., stakeholders and decision makers) as well as social institutions and communities. Such individuals and institutions are termed agents. For example, how do agents respond to economic incentives, water stresses, extreme events, risk, and environmental regulations? How do agents think about and use scientific information (e.g., climate/weather forecast) and other sources of information (e.g., environmental education)? Development of an understanding of the divergence of opinions and heterogeneity among agents and their evolution over time is now only in a conceptual stage; there is a tremendous need for empirical studies.

The coupling of agent-based models (ABMs) which describe the human decision process with existing biophysical models for the natural system is an attractive challenge for scientists, including hydrologists. An ABM does not assume homogenous behavior (as a traditional water resource system optimization model usually does) and thus it can represent the agents involved in a water resources system more realistically [*Zhao et al*., 2013; *Yang et al*., 2009]. A true or complete CNHS model will require the coupling of a distributed environmental model (e.g., a distributed hydrologic model) and a distributed institutional model (e.g., an ABM), with the interactions between human and natural components modeled at appropriate spatial and temporal scales.

ABM approaches are still in their infancy in part because their validation is difficult due to the lack of data or lack of mechanisms [*Windrum et al*., 2007]; and some agent behaviors are either unknown or unmeasurable using existing methods. There is a critical need to derive behavioral rules using data from multiple sources with multiple formats (i.e., qualitative and quantitative, natural randomness and the various degree of uncertainties, various temporal and spatial scales). Thus, developments in "big data" described below are critical to the development of future ABM approaches for CNHS, especially in terms of capturing the rules of agents' behavior over time.

5.1. Decision-Oriented Watershed Management Models

Watersheds are coupled natural-human systems (CNHS's) characterized by interactions between human activities and natural processes crossing a broad range of spatial and temporal scales. For the integrated management of watersheds, there is a need for the development of comprehensive decision-oriented watershed management models as opposed to the incremental enhancement of existing watershed-based hydrologic models. *Zoltay et al*. [2010] refer to such models as integrated watershed management models (IWMMs) which they define as models that:

1. are developed for modeling watershed management alternatives with the goal of understanding the effects of management decisions on the watershed system in order to support decision making and stakeholder negotiations;
2. integrate all relevant components of the natural watershed, human water system, and applicable management tools; and
3. are formulated in a systems context, with decision-oriented management optimization capabilities to aid in the selection of promising combinations of management strategies;
4. are generic and general models that are technically and financially accessible to allow their application to watersheds with diverse characteristics.

The initial watershed management model introduced by *Zoltay et al*. [2010] has quickly evolved into a model termed the Watershed Management Optimization Support Tool (WMOST) developed and distributed by the U.S. Environmental Protection Agency [*U.S. EPA*, 2013]. Other examples of decision-oriented integrated watershed management models include, but are not limited to, the Water Evaluation and Planning (WEAP) [*Yates et al*., 2005] model and WaterWare [*Jamieson and Fedra*, 1996].

5.2. Reflections—The Future of Integrated Risk-Based Water Management

In summary, natural systems hydrology is incomplete due to its lack of accounting for the human modification of fluxes that is emerging as substantial in many places. We have highlighted that the social and institutional systems as well as the economics of water use are interconnected and continuously changing, even as we experience human-induced hydrologic change. The hydrologic changes we have experienced will, over time, lead to changes in management practices, and hence to changes in hydrology.

As an outgrowth of the IPCC process for climate change impact assessment, a variety of integrated assessment models [e.g., *Koji et al*., 2012] have been developed. A key need that has been identified for the improvement of such integrated assessment models is to incorporate potential adaptation strategies to climate change, as well as the response of the vegetation and other biophysical changes directly into the models, as part of an interactive human-biophysical earth system modeling capability. We find it useful to learn from this experience, even for watershed scale modeling, and suggest that hydrologic modelers think about the possible evolution of water resources management models and strategies as they consider changing hydrologic conditions in response to climate or land use or other economic activity. In addition, market-based mechanisms can be brought into the model, including the integration of financial risk management strategies, option contracts, forward contracts, cap and trade, conservation credits, and other mechanisms for resource allocation and regulation, as well as disruptive technologies for inexpensive filtration and treatment, or water use efficiency improvement.

In the past, the central planner model has dominated, and the Harvard Water Program and others simulated a rational economic actor making decisions, where the normative aspect of decision making and management could be encoded into a finite set of rules or objectives, and an optimal solution derived subject to physical and operational constraints. As indicated earlier, this paradigm has evolved to modeling the behavior of multiple classes of interacting decision makers (known as agents), such as farmers and miners, in the framework of agent-based models, and their spatial interactions may even be modeled through Cellular Automata or network models. These are important developments, but they need to be constrained by possible scenarios or descriptions of the evolution of a water management paradigm that may not mimic the current regulatory or investment situation. Further, economists have begun to recognize that the classical model of rational decision making may not correspond to the decision-making process of actual people and institutions. The psychological basis for decision making, as advanced through prospect theory [*Kahneman and Tversky*, 1979], considers problem framing and risk perception, as encapsulated in the perceived probabilities of favorable and adverse outcomes and argues that these factors may be more important than expected net benefits or expected utility in real life decisions. An example of such an outcome is presented by [*Rayner et al*., 2005] in the context of the use of probabilistic seasonal climate forecasts by water resource managers. They contend that even when climate forecasts may be reasonably accurate, and suggest a high expected return for a departure from business as usual, water managers are reluctant to use them. Their decision is apparently guided by the asymmetry in the perceived outcomes. If they make a decision to release water from a reservoir anticipating a flood, and the decision turns out to be a good one, the likely reward for the individual is a commendation or award. On the other hand if it turns out to be a bad decision, the likely consequence could be termination of employment or at the very least a publicized failure. Considering both outcomes and their associated likelihood is of paramount importance in the decision process, analogous to considering the consequences and likelihood of underpreparation and overpreparation corresponding to climate adaptation challenges [see *Vogel et al*., 2013; *Rosner et al*., 2014].

6. Proposition 3: Knowledge Discovery Through "Big Data" Shows Promise for Understanding the Coupled Human/Hydrologic System

Water intersects with nearly all sectors of socioeconomic endeavors, climate, geosciences, and ecology. Thus, a holistic study of water in any watershed or region is a multiscale, multimedia, multidimensional study. Even at a high degree of idealization, this results in a model of a complex system whose evolution over different time scales depends on attributes that are endogenous as well as exogenous to the system definition, and the exogenous factors (e.g., climate, energy, health, food, social dynamics, and ecology) typically have their own rules of evolution. Consequently, any "model" that attempts to describe a subset of this complex system will require considerable effort and may even develop as a subfield (i.e., sociohydrology and ecohydrology), yet be limited in its scope. A place-based water resource study is defined as much by its spatial scale and boundaries as by its exogenous drivers. Invariably, as we attempt to integrate additional subfields into hydrology (e.g., ecohydrology and sociohydrology), the more we learn, the more we discover what we do not know. This richness of behavior makes the human, water, and climate story incredibly fascinating, and begs for deeper thinking into the very core of what our nearly unique planet can evolve to. Numerous subfields of hydrology have been advanced, yet little progress has been made toward a unified understanding of human/hydrologic systems. Below, we outline how this could change under an "active" paradigm that treats the human and hydrologic environments as a single integrated system.

7. The Global Data Services Revolution

A fully integrated and coupled model of hydrologic and human systems, as we suggest here, will require detailed observations of the biophysical and social processes contained within these systems. Data access and management for hydrology is now evolving toward a global data access infrastructure based upon worldwide standards for the structure of data services, catalogs, and data formats. One example of this is the Consortium of Universities for the Advancement of Hydrologic Science, Inc. hydrologic information system (CUAHSI HIS) [*Maidment et al*., 2009]. In much the same way that we use the web browsers to find documents and web pages, CUAHSI HIS provides analogous access to hydrologic data. A data access client acts like a web browser for data, with data and a data catalog available via services in a Service Oriented Architecture (SOA). An HIS client (such as Hydrodesktop, http://www.hydrodesktop.org or the NANOOS data explorer [http://www.nanoos.org, http://nvs.nanoos.org/Explorer]) interprets the water data presentation language and presents the user with formatted data and metadata in the form of tables or charts. CUAHSI also maintains a metadata catalog of hydrologic and other time series data (http://hiscentral.cuahsi.org) that HIS clients can search to discover data from over 100 different publishers. These publishers create internet servers for data based upon the WaterOneFlow service standard adopted by CUAHSI.

The development and adoption of HIS has been accelerated by the development of internationally accepted standards for WaterML through a joint effort of the Open Geospatial Consortium [see *OGC WaterML*, 2014] and the World Meteorological Organization. The CUAHSI HIS [*WMO*, 2012] is on track to being adopted as an internationally recognized approach for discovery and transmission of hydrologic time series data. Under the auspices of the Global Earth Observing System of Systems (GEOSS), prototype data services using CUAHSI HIS to provide OGC standard services have been established on five continents (Pecora, personal communication, 2014). CUAHSI and the U.S. Geological Survey (USGS) plan to adopt *OGC WaterML* [2014] service standards and thus become part of a worldwide move toward global access to water data. Metadata catalogs are being developed in different regions of the globe, also using *OGC WaterML* [2014] standard protocols that will interoperate to provide the user with seamless access to data around the globe.

As scientists learn to exploit these data services in their research, opportunities open up for both discovery of mechanistic insights through observing patterns in large data sets and making data-hungry techniques such as data assimilation easier to execute for hydrologic prediction. These data services provide easy access to the vast amount of in situ data being collected around the world. At the same time, satellite-based remote sensing is creating new global data sets on changes in water storage (through measurement of gravity), soil moisture, and global precipitation estimates. Hydrology and water resources engineering is on the cusp of entering the "big data" era that promises to fundamentally alter the way we do research and enable more of the interdisciplinary research on human interactions with the water cycle that is needed to create truly coupled and integrated human/hydrological modeling systems.

7.1. Reflections—Big Data-Driven Knowledge Discovery

The analytical and conceptual advances on the biophysical and social aspects of hydrology seem to have reached an impasse. The big data revolution has arrived at the right time. With the explosion of our capability to monitor, store, and access large quantities of data (Big Data) in real time, and in archives, enormous opportunities exist to reveal patterns, trends, and associations, especially relating to human behavior and their interactions with hydrologic processes. Climatology, biomedical science, finance, behavioral sciences, and computer science disciplines have extensive expertise in mining large data sets, often in real time, to understand relationships between processes which continue to lead to rapid advances in these fields. Some recent examples in hydrology include: using multivariate data sets to identify global moisture sources, transport and delivery mechanisms which produce large hydrologic hazards such as floods and snow storms [e.g., *Lu et al*., 2013; *Nakamura et al*., 2013].

While a great deal of investment is now being made to manage, maintain and analyze large data sets, the era of "Big Data" also poses enormous challenges to the hydrologic community, a few of which we outline here.

Human water use data may still be the most unreliable source of information needed to model the hydrologic cycle [*National Research Council*, 2002]. Challenges and opportunities are associated with the need for both data and monitoring of the social aspects of water resource systems [*Braden et al*., 2009]. Fortunately, the current emphasis on Big Data is likely to result in new sources of information at the boundaries of the biophysical, social, and engineering sciences, which is critically needed to fill existing knowledge gaps and to address the interconnectedness between the disciplines. New observations and monitoring systems with improved spatial and temporal resolution, particularly on human water use, infrastructure, and land development, are critically needed along with data mining technology to better illustrate human footprints in hydrologic systems.

Perhaps, the most critical need concerning "Big Data" involves providing an educational foundation in the "theory of data" for future generations of hydrologists. Just as fluid mechanics, engineering and various branches of the earth and social sciences have provided an educational foundation for previous generations of hydrologists, universities need to give greater attention to providing an analogous theoretical educational foundation for "Big Data" which at its core involves both the theory of probability and computer science. Only after a firm foundation in those areas can future hydrologists become proficient in summarizing and analyzing "Big Data" using advances in the fields of statistics, machine learning, signal processing, and data mining. Unfortunately, hydrology and water resources curricula are often quite narrow, focusing largely on the physical processes from a classical Newtonian perspective, with rather limited attention to issues of scale averaging, appropriateness of the equations being used at a given scale, and with even less attention given to socioeconomic issues. As we have described and hopefully persuaded the community, future hydrology researchers will need a broad education context covering physical processes, socioeconomic systems, and the ability to analyze and model Big Data. We cannot wait any further to introduce this needed change in the curriculum.

8. Hydrologic Planning Under the Continuum of Uncertainty and True Uncertainty

As hydrologists, we are aware of the initial waxing and then waning interest in floods and droughts in their aftermath. There is often some measure of surprise associated with such events, in spite of the facts that we: define a priori, such events to be rare, usually have plausible estimates of their probability, and have even developed a rather advanced state of flood and drought preparedness in many regions. Similarly, economists exhibit a waxing and then waning interest in severe market downturns in their aftermath, and after the 1929 depression, *Keynes* [1937] extended the concept of "uncertainty," introduced previously by *Knight* [1921], which is now widely referred to by economists, as "true uncertainty" [*Davidson*, 1991] for situations or events in which there is "no scientific basis on which to form any calculable probability whatever" [*Keynes*, 1937, p. 217]. More recently, events which are subject to "true uncertainty," have been associated with terms such as "surprise," "deep uncertainty," "total ignorance," and "black swan events." We do not wish to debate which term is most appropriate, so instead we use the term "true uncertainty" because it has a rich supporting literature going back nearly a century [see *Hodgson*, 2011, for a recent survey of this concept in economics].

The sense in which economists have used the term "true uncertainty" is that in which, for example, the prospect of a water conflict leading to a Middle East war is uncertain, or the impact of virtual water trade on global food prices, or the degree of infrastructure adaptation due to climate change needed over the next 50 years. The rich and continuing economics literature relating to true uncertainty has not been discussed in the hydrology and water resources literature, though *Fiering and Kindler* [1987] alluded to it in their discussion of "surprise" defined as the psychological state following the realization of the unanticipated or unexpected. Again, as with true uncertainty, the notion of potential surprise has a scientific basis which began with *Weaver's* [1948] attempt to develop a probabilistic index of potential surprise and *Shackle's* [1949] (nonprobabilistic) theory of expectation decision making in a world of ignorance.

We contend that a distinction needs to be made between uncertainty as it has come be understood in our field and "true" uncertainty which implies that a probabilistic analysis may not even be relevant to the problem of concern. True uncertainty implies that the consequences of a potential event are unknown, or perhaps unknowable, thus we cannot assign probabilities to the consequences such that the probabilities sum to unity. Extending *Davidson's* [1991] comments on economic systems to water resource systems, in circumstances of true uncertainty, we would not be able to specify all the impacts of the various adaptation strategies open to us. If some impacts are unknown, we cannot assign probabilities to the impacts such that they sum to unity, as required. One could force the sum to equal unity, but what meaning would such a probability distribution have upon learning of another outcome?

Surely, water management decisions are made under uncertainty and we do not argue that uncertainty prevails. What is arguable is the nature of that uncertainty. Nearly, all focus in the past has been on mapping uncertainties into probability functions. Surely, hydrologic uncertainty is well addressed with probability functions, in part because physical processes are in step with mechanical clocks. However, the same cannot be said in reference to water resource issues where hydrology is linked to economics and politics both of which unfold in historical time. In historical time, subject to true uncertainties, it would be presumptuous to assume that the future is mirrored by the past because decisions are made in a state of incomplete knowledge (ignorance), where economic processes are nonergodic, and therefore what is, is not what was, nor what will be. In such a world, probability, objective or epistemic, seemingly can play no role in the making of decisions, either because the probabilities do not exist or if they do exist, they are unmeasurable.

Fiering and Kindler [1987] provide a taxonomy of potential surprise including "those events which had been imagined but consciously rejected as not possible and those which had never entered into the planner's imagination and which had never been conceived or considered." It is important to recognize that both counter-expected and unexpected events can occur for entirely different reasons. If true uncertainty and potential surprise cannot be addressed in probabilistic terms, approaches to address such concerns will, of necessity, be quite different from our traditional methods of uncertainty analysis employed in hydrology. We do not see the distinction between uncertainty and true uncertainty as black and white, but rather a continuum between nearly pure determinism and total ignorance, as elaborated by *Walker et al.* [2003]. Thus, a continuum of hydrologic methods will need to be brought to bear to reduce those hydrologic risks posed by both uncertainty and true uncertainty.

9. Summary: Future Directions for Hydrology for the Benefit of Society

Sustainable development and resilience have emerged as crosscutting themes in much of the academic literature. They reflect both the tremendous progress made in the twentieth century to reduce hunger and poverty, and to improve incomes and the quality of life, while stimulating a record growth of population. They also reflect the dramatic change in the face of the earth, portrayed in our changing climate, hydrology, landscape, and oceans. It appears that we have successfully increased our apparent carrying capacity with respect to the primary historical resource constraints, but unfortunately introduced the environment as a new resource constraint for the planet's carrying capacity. Nowhere is this more evident than in the realm of water, which is a resource, an environment and also a natural hazard. A clear lesson that has emerged is that water, climate, energy, food, society, industry, environment, and economy are inexorably intertwined, and an understanding of the long-term coevolution of their states is needed for sustainable development and resilience. This is essentially what much of the discussion in this paper has documented.

So how does one develop a direction for hydrology that goes beyond the identification of structural relationships between specific variables, and using them in models with parameter identification from relatively sparse data, to exploring our long-term water future in a world where a lot of other factors that determine that future are also changing? Here are some suggestions which have emerged directly from our discussions:

1. *Improved Prediction Models and Uncertainty Analysis for Water Management*. Decision making on water management increasingly needs to consider the water risk exposure and hence the resulting behavior of both the central manager and the large number of users. This greatly expands the domain of prediction of the human-hydrologic system evolution, and of the potential exposure of the deep or true uncertainty that is difficult to quantify. While we have made progress on aspects of hydrologic prediction, a grand opportunity awaits us in documenting and understanding human water use and risk aversion behavior, and its role in shaping the ever changing world we live in. Hydrologists need to develop a diagnostic

capability that can lead to a predictive theory of factors that determine water availability and use in any particular socioeconomic, biophysical, and institutional setting. Improved hydrologic predictions can improve water management because it can lead to improved decisions relating to water diversions, pollutant loadings, infrastructure, as well as the potential choices for economic activities in a region. In the twentieth century, with a focus on infrastructure development and allocation, we developed the capacity for project level analysis, where the demands for water services were essentially assumed a priori, and the projects were sized accordingly. To develop an understanding of hydrology in river basins and countries, we now need to extend these analyses to understand how the drivers of demand themselves may evolve, or more importantly should be guided, given anticipated long-term hydrologic outcomes. Our focus here has been on a discussion of the improvements in hydrologic models which in turn can lead to improvements in water management to enable sustainable development. Thus, it is not enough to simply improve hydrologic prediction models, such models must be embedded into a risk-based water management decision framework. Thus, improvements in hydrologic prediction must include a full decision-oriented accounting for prediction uncertainty, and probabilistic prediction intervals are not enough. *Rosner et al*. [2014] provide an example of embedding a very naive hydrologic trend prediction model into a risk-based decision model, including prediction uncertainty in the form of the likelihood of under/over preparation. Thus, arguments over whether or not a hydrologic prediction model is suitable for use in water management are moot, unless such arguments include an evaluation of such hydrologic prediction models within a complete risk-based decision-oriented framework.

2. *Improvements in Decision and Risk Analysis*. We have argued that in the context of a sustainable development and resilience framework, which is necessarily long term, then the institutional and social structure under which decisions are made, the actors (agents) involved in decision making, the social values that determine good decisions, and the technological, biophysical, and economic settings under which decisions are made, may all change over time. In such a setting, a traditional risk-based design and operation-based approach for water systems is not adequate, since the probability of exposure and the probability of loss, as well as the benefits assumed for a particular system will change with time and exhibit some degree of coupling. As market-based instruments for climate risk, and for water allocation become more prevalent, there may be fundamental changes in water use, possibly stimulating technical innovation toward improved water use efficiency and reuse strategies, as well as the transfer of catastrophic risk to financial instruments from structural solutions currently used for things like flood control. Further, the institutional structure for water services may evolve from that of a centralized manager and system, to more distributed water resource systems operated by multiple vendors and agents. All of these imply an analysis of risk that needs to be considered for design and operation of systems under both short and long-term analysis, where the probabilities of interest for risk characterization will change with time, possibly in some structured fashion. Thus, we anticipate that a fundamental change in risk and decision analysis will emerge as the paradigm for decision making in this new heterogeneous water environment. As we have discussed, such analyses will of necessity consider the continuum which exists between (1) perfect knowledge, (2) traditional notions of uncertainty, and (3) "true uncertainty" corresponding to situations in which the decision makers simply do not have a clue as to what is going to happen, thus probability theory is irrelevant. Thus, a new suite of decision-oriented modeling approaches will need to be brought to bear to reduce hydrologic risks posed by hazards associated along a continuum from perfect knowledge, to uncertainty, to true uncertainty. This new form of risk and decision analysis will also need to consider multiple time scales, multiple enterprises, and be based on a calibration of conditional probability distributions that consider the evolution of different factors that are important, and hence allow the probabilities of exposure, loss and benefit streams to change as those causal variables, and hence the underlying state of our water resource systems evolve. Given our past history of systems analysis in a stationary world where water was primarily articulated as a public good, it is to be expected that of all the earth and environmental sciences, hydrologists are poised to provide the leadership in providing both implementable and sustainable decision science for the changing world.

3. *Improved Information Systems for Water Withdrawals and Return Flows*. We have emphasized the need for hydrologists to develop comprehensive data and information systems which summarize factors that determine water use, return flows and diversions under varying climate, socioeconomic, and institutional settings. While we continue to develop a capability for monitoring both water quality and quantity, there

is great uncertainty as to water use, return flows, and diversions because there is little formal data collection. Such data is sorely needed to improve the efficiency of water use under changes in: pricing, regulatory structures, water trading or allocation schemes, social and economic values, climate, energy use, and ecological systems.

4. *Improved Information Systems and Inference Engines for Integrated Models*. We have reviewed the limitations and increasing importance of integrated assessment models that link existing domain models to analyze potential scenarios of future outcomes, in a climate change context. We have also documented the critical importance of developments in "big data" to the development of future agent-based modeling approaches for coupled human/hydrologic systems, especially in terms of capturing the rules of agents' behavior over time. We have also highlighted how recent advances in data mining now enable discovery and development of new hydrologic models by explicitly accounting for both hydrologic and human variables. Hydrologists now need to invest in new conceptual formulations that allow a clear mapping of potential cause and affect vis-à-vis coupled hydrologic, socioeconomic, and ecologic outcomes that may emerge in the long run under varying assumptions as to demographic, climate, economic, agriculture, and energy parameters. First, significant long-term data sets on the key indicator variables for these causal networks should be developed. Once such information is available, data-based inference is needed on (a) the emergent patterns across the indicator variables, (b) thresholds in key variables that lead to regime changes in the dynamics of the integrated system, (c) sensitivities and conditional probabilities that determine the information transmission across the causal chain and across spatial and temporal scales at which the system evolves, and (d) stable and unstable regimes and equilibria of the system. We emphasize the need for a data-based approach to probabilistic inference on space-time causal networks, as opposed to a purely deterministic model-based approach where a collection of domain models is integrated and some aspect of parameter uncertainty for each domain model is addressed through a calibration process, and some data assimilation is performed. These traditional approaches to integrated assessment do not, in our view, reflect a robust approach to understanding complex, interacting systems where the evolution across system boundaries is determined by a few variables that determine the cross system and cross space/time feedbacks.

5. *Global Perspectives Are Now Essential*. Much of hydrology has focused on watershed and aquifer processes and associated models. This is useful and needed. However, from a sustainability and resilience perspective, long-term climate variations and their local manifestation are important to understand, since decadal and longer wet or dry climate regimes can have a significant influence on shaping water use, hazard mitigation, and local hydrologic watershed functions. Developing and using paleoclimate information may be useful to inform how hydrologic transitions may occur, which is important to understand the dynamics of the long-term evolution, even for watershed scale hydrologic information. Such paleoclimate information can also put the evolution of hydrologic systems into the context of global climate models such as the El Niño Southern Oscillation, the Atlantic Multidecadal Oscillation, and their influence on regional flood, drought and precipitation intermittence and intensity, and water use attributes. Similarly, an understanding of global trade, and its determination of which water use activities may evolve or devolve in a particular watershed, in response to globalization of supply chains, is an example of factors that hydrologists need to consider in a long-term analysis. Further, radical technological changes that can change the water-use regime (e.g., high-performance filters that make water reuse and treatment inexpensive, or artificial synthesis of hydrocarbons and proteins to replace traditional agriculture), and become globally available, could dramatically change hydrologic regimes. Such innovations are inevitable, and need to be considered in any forward looking adaptation analysis, especially in the highly water stressed regions in the world. Indeed, the demand for hydrologists and water services is likely to be the highest in such regions, and it is incumbent upon us to both understand and shape their future. For example, global issues such as world food trade have been shown to interact with basin-level hydrology and water resources engineering [e.g., *Rosegrant et al*., 2002].

6. *Institutional Reform for Emerging Water Resources Management Problems*. We have speculated that in the 21st century, private investment in water development and operations may dominate the traditional centralized federal and state funding and operation of projects, and given the emerging water scarcity exigencies, we may be on the verge of a significant paradigm change in water resources management. The World Economic Forum's risk perception review that polls the CEO's and CFO's of the major global

corporations has rated water scarcity as one of the top 2 or 3 global risks for each of the last 5 years. It is the top risk in terms of potential impact and in the top 5 in terms of likelihood, in the recently released 2015 global survey [*World Economic Forum*, 2015]. It is likely that increasing private sector attention to water management will translate into greater disclosure, accounting and analysis of water use and its economic value for certain agents. This may lead to efforts to streamline supply chains in the same way that has been emerging in the energy sector. The increased engagement of the financial community in water management may also bring innovations in financial risk management tied to water system operation, and in the impacts of floods and droughts. Both the public sector and ecological advocates will of course need to help define how the needs of the economically disadvantaged sectors and biological communities should to be met. In the process, demands for much more hydrologic data, an assessment of the potential impacts of best management practices, and for scenario analyses for the future will emerge. These will help define the modeling directions, precision and use for the integrated water management models we will need in the near future.

7. *Improved Water Curriculum*. We have discussed the surprisingly limited advances, to date, associated with our understanding of the role of water in the social sciences, and vice versa. Water law, water economics, water policy, water diplomacy, water management, and water and development have not emerged in the same way that the corresponding study of climate and society, or energy and society, or food systems and their relationship to poverty and development, has emerged as academic lines of inquiry. As we have described and hopefully persuaded the community, future hydrology researchers will need a much broader education than they have been accustomed to, covering physical processes, socioeconomic systems, and the ability to analyze and model Big Data. We cannot wait any further to introduce this needed change into the curriculum.

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