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Overview

Progress in socio-hydrology: a meta-analysis of challenges and opportunities

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Socio-hydrology was introduced 4 years ago into the scientific lexicon, and elicited several reactions about the meaning and originality of the concept. However, there has also been much activity triggered by the original paper, including further commentaries that clarified the definitions, and several papers that acted on the definitions, and through these activities further clarified and illustrated the meaning and usefulness of socio-hydrology for understanding coupled human–water systems and to assist with sustainable water management. This paper restates the case for socio-hydrology by articulating the need to consider the two-way feedbacks between human and water systems in order to explain puzzles, paradoxes, and unintended consequences that arise in the context of water management, and to suggest ways to avoid or overcome these challenges. The paper then presents a critical review of past research on socio-hydrology through the prism of historical, comparative, and process socio-hydrology, documenting both the progress made and the challenges faced. Much of the work done so far has involved studies of socio-hydrological systems in spatially isolated domains (e.g., river basins), and phenomena that involve emergent patterns in the time domain. The modeling studies so far have involved testing hypotheses about how these temporal patterns arise. An important feature that distinguishes socio-hydrology from other related fields is the importance of allowing human agency (e.g., socioeconomics, technology, norms, and values) to be endogenous to the systems. This paper articulates the need to extend socio-hydrology to explore phenomena in space and in space-time, as the world becomes increasingly globalized and human–water systems become highly interconnected. The endogenization of human agency, in terms of values and norms, technology, economics, and trade must now be extended to space and to space-time. This is a necessity, and a challenge, for water sustainability, but presents exciting opportunities for further research. © 2016 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

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INTRODUCTION

Humans have been exploiting the Earth's natural resources at an accelerating pace ever since intense economic activity was triggered by the industrial revolution. This exploitation of the Earth's natural resources facilitated, and was in turn facilitated by, technological innovations. These innovations included extraction of iron ore, the steam engine, and faster ships, railroads, and several other means

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subsequently that connected people worldwide through trade. Concerted ambitions of humans in different parts of the world with their unique niches, now connected through trade, fuelled the fiery thirst for more affluence. This added to the pressure of sustaining the growing human population on the Earth's natural resources such as land and water.[1]

Human demand for food, water, and energy has now grown to the point that humans are in sharp competition with nature, and can no longer afford to take for granted nature's ability to restore itself. Humans are now threatening their own future survival on the planet.[2] There is a global water crisis, manifesting itself in different ways in different parts of the world, fuelling other related crises and conflicts. Unregulated extraction of water for human consumption is having several unintended consequences[3] such as land subsidence, saltwater intrusion, water conflicts between riparian states, altered timing and peaks of downstream flows, including continental flows into the oceans,[4] negative downwind consequences of deforestation,[5] and shifting patterns of precipitation.[6]

These negative consequences of the water crisis remind us that: (1) humans themselves have played a key role in generating such crises across the globe, (2) past human actions affect the present and future availability of water resources, (3) water crises are rarely local, i.e., they transcend the isolated actions of humans at any given location. These are sobering messages for the science of hydrology which has long ignored the role of humans, necessitating the evolution of the science to face up to these challenges. In particular, they demand a change in the way the science of hydrology accounts for humans and human actions. In the emergent Anthropocene, humans can no longer be considered as mere external drivers or boundary conditions in hydrologic systems; rather, humans must be considered as central to the hydrological system, i.e., endogenous, to the coupled human–water system.[7]

EMERGENCE OF SOCIO-HYDROLOGY

The need to have humans as central to the coupled human–water system has been recognized for some time. This is evident from the existence of other fields of study such as hydrosociology and hydroeconomics, which also study coupled human–water systems. Falkenmark[8] motivated the field of hydrosociology by the need to understand how human actions alter water systems (i.e., water projects leading to social consequences). The assessment of the societal impacts of a physical water system may be the subject matter of hydrosociology. Hydroeconomics and hydroeconomic modeling, on the other hand, are aimed at either optimizing the economic objectives of a water system, such as conjunctive use of groundwater and infrastructure,[9] cost-effective environmental flows in the context of binational river management,[10] and optimal water conservation and infrastructure expansion.[11]

In these ways, hydroeconomics and hydrosociology operationalize economic concepts and societal impact assessment, respectively, by incorporating them at the heart of water management.[8,12,13] By doing so, these approaches respond to 'what if' scenario-based questions, such as what would be the effect of salinity on the economic value of water,[14] or what would be the societal impact of infrastructure expansion, such as the building of new dams.[8] Long-term socioeconomic (such as population, wealth, etc) and water infrastructure scenarios (e.g., demand projections and water policy) are needed to assess long-term impacts of societal decisions on water availability and food security. However, these scenarios remain 'exogenous,' i.e., prescribed boundary conditions that nevertheless may change over time.

The new field of socio-hydrology complements the strengths of such scenario-based studies by going further and proposing to 'endogenize' the generation of such scenarios. It does so by not just having humans as central to coupled human–water systems but also by considering bidirectional feedbacks between humans and the water environment, which might generate new emergent dynamics. For example, in an agricultural context, patterns of population, water availability, and food production may emerge due to intrinsic dynamics of the water–food system, rather than being externally prescribed. The short time-scale interactions among population, water extraction, and food production influence the potential for longer-term population growth or decline and their feedback on future water extraction and food production. Emergent phenomena such as the growth and decline of population and food production in water scarce basins can be interpreted in terms of interactions between short and long time-scale processes.[13]

The pursuit of socio-hydrology is aimed at understanding and interpreting diverse phenomena instead of mere case studies that do not have an explicit drive toward arriving at a broader, generalized understanding. In this way socio-hydrology follows the more *positivist* approach of trying to understand the dynamics of coupled human–water systems,[13,15] as opposed to the *normative* approach aimed at solving concrete water management problems. It relies on the cyclic method of hypothesis generation→observations→hypothesis update (i.e., the method of scientific inquiry) to analyze both individual case studies and comparative studies. It seeks 'regularity' or 'recurrence' in social behavior, development, or change in respect of water that is independent of space and time[16] (see arguments of Prichard-Evans and others in Ref 17, p. 27, in context of social sciences). One should also acknowledge that words such as laws and prediction take on different meanings in the context of socio-hydrology,[18] just as it has in social sciences.[19]

The search for general patterns distinguishes socio-hydrology from the humanities fields such as historical assessment and environmental history, which eschew the search of regularity and are more focused on studying particular times and places in the past. Socio-hydrology is similar in spirit to social and ecological anthropology,[17,20] and classical and contemporary sociological theory,[21–23] which emphasize the use of the comparative method aimed at studying structures and processes to 'formulate and validate statements about the conditions of existence of social systems and the regularities that are observable in social change'[19] (see also page 50 of Ref 17). In this way socio-hydrology diverges from fields that propose the study of ecosystems as systems that are inherently coupled with political (e.g., political ecology), economic (e.g., ecological economics), or social systems (e.g., social ecology). All such fields study coupled human–environment systems but in their respective contexts. For example, the treatment of a water body as a system and water as a resource unit (within the proposed nested socio-ecological systems framework) in Ostrom[24] can be restrictive in the context of coupled human–water systems. Some rely on existing theories such as complexity theory and nonlinear system dynamics. Few,[24] to our knowledge or belief, propose rigorous implementation of the comparative method across a diversity of locations and times for the purpose of discovering fundamental or generalizable properties of coupled human–water systems.

Socio-hydrology, as a science that studies the interactions of society and water, seeks regularities in social behavior or societal development that may emerge from their coevolution with the hydrological system. Historical analysis is important for socio-hydrology to understand emergent phenomena because analysis of the past at different locations helps to discover fundamental principles behind coupled human–water systems. Socio-hydrology can accommodate the agonistic–antagonistic mode of interdisciplinary research[25] that requires a self-critical view of hypotheses posed in the analysis of coupled human–water systems.[26] The pursuit of understanding of socio-hydrologic phenomena based on the cyclic approach involved in the scientific method is admittedly prone to subjectivities of the researcher—the key ingredient of which is the speculation of the researchers involved.[17] As a nascent field, socio-hydrology has only recently begun to understand and interpret diverse phenomena that emerge from coupled human–water systems[27] and to acknowledge the pitfalls in applying the scientific method under these circumstances.

EMERGENT PHENOMENA: FOUNDATION OF THE SCIENCE OF SOCIO-HYDROLOGY

As already mentioned, the subject matter of socio-hydrology are the many diverse phenomena that emerge in different coupled human–water systems around the world. They may manifest as puzzles, paradoxes, or patterns, exhibiting similarities in spite of distinct hydroclimatic, eco-environmental, and socioeconomic features. Examples include the agrarian crisis in booming emerging economies such as India, the peaking in water resource availability as basins develop, and increasing levee heights in urban environments even at the expense of increased flood risk. The science of socio-hydrology aims to interpret such phenomena in terms of dynamic two-way feedbacks through the method of scientific inquiry, and to develop generalized understanding that can connect diverse phenomena across many places and times.

Phenomena emerge in coupled systems due to complex interactions between humans and their water environment. Distress of marginal farmers in India, in spite of a booming economy, is an outcome that emerges due to complex feedbacks between their biophysical (e.g., water, soil fertility, and fodder production), social (e.g., knowledge generation), and capital (e.g., tractors, finance) stocks.[28] High hydroclimatic variability adversely affects crop production of small-scale farmers if they are unable to smooth out the effect of the variability on their well-being, such as income and health, due to lack of social safety nets. Repeated crop failure leads to low levels of capital that is insufficient to buy labor, fertilizers, or high yielding crop varieties that otherwise may help farmers to stabilize crop production. As Figure 1 argues, understanding the complex feedbacks between water resource availability, crop production, and income under volatile commodity markets is a prerequisite to explaining the tragedies

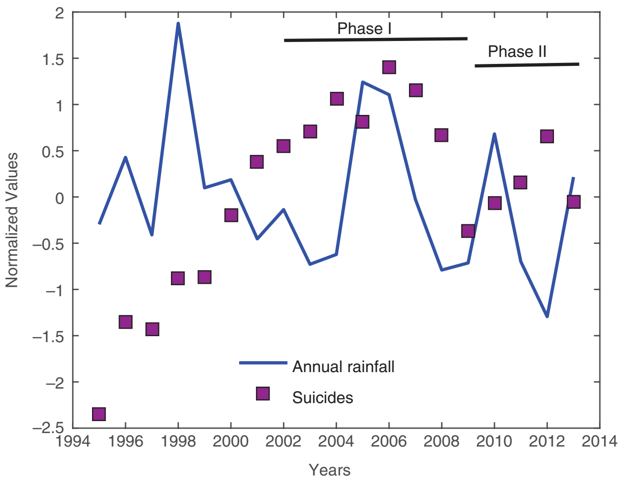

FIGURE 1 | Annual rainfall and farmer suicide rates for Maharashtra state in India. The time series has been normalized by subtracting the mean from the time series and dividing by its standard deviation. Two phases are shown, Phase 1, when suicide rate counter-intuitively rises and falls along with annual rainfall. In Phase II, the suicide rate does not correlate well with annual rainfall. The two phases demonstrate that there is more to the dynamics of farmer suicides than pattern of annual rainfall. The figure shows a phenomenon that often emerges from small holder systems in emerging economies, where more and more farmers can be under distress in spite of high economic growth rates. Further it shows that pattern of water availability on its own cannot explain the pattern of farmers suicides in Maharashtra. Sources: www.tropmet.res.in, https://psainath.org/maharashtra-crosses-60000-farm-suicides/.

that often beset many small-scale farmers in developing countries.

Consider two basin-scale phenomena, whereby water quality degradation[29] and water use[30] first rise and then decline even under increasing population pressure. Partial analyses, such as impact assessment of population growth on water quality and water use, are insufficient to explain the phenomena. The feedback of environmental degradation on the use of water resources via increased environmental awareness in the community and technological innovation can possibly explain them better.

Basin-scale communities often swing between water extraction for food production or water control for urban development in the initial stages and then efforts to mitigate and reverse the consequent degradation of the riparian environment in the later stages.[31,32] This is a 'pendulum swing' that may be explained by counteracting productive and restorative forces, mediated through technology, environmental awareness, and the intervention of governance institutions. Institutions or community organizations such as green movements emerge in response to degrading environmental quality, catalyzing innovation in the use of green technology such as water reuse for irrigation and industrial use. Environmental degradation often engenders basin-scale hydrosolidarity, which is the will of all people within a basin to make a determined effort to change the way water has been used in the past. This may lead to emergence of institutions, such as basin-scale management authorities, that then enable communication of the environmental degradation back to the agents behind the productive forces.[16] The Sandoz accident in 1986 in Europe is one such example.[33] The accident brought together all riparian states of the Rhine river basin to strengthen the authority of International Commission for the Protection of the Rhine to monitor and forewarn any pollution event along the Rhine. Such a feedback has brought about a dramatic change in Rhine river water quality, a positive development that could not have been foreseen without the institutional feedbacks that accidents such as Sandoz bring. Contrast this with the case of Aral Sea, as illustrated in Figure 2, which dried out due to weak institutions in spite of community awareness of the consequences of unregulated water use.[34]

Rigid water governance may lead to another set of unintended consequences when new technologies are introduced. Agricultural water that is 'saved' through irrigation efficiency improvements may end up being used in other sectors such as industrial and municipal water use,[35] wiping out the gains of using such technology. Water saving through smart irrigation technology such as drip irrigation may give an impression of abundance of water to farmers, often leading to adoption of water intensive crops or diversion of saved water to industrial or domestic use. Exploring the space of possible water uses, technology and institutions, including potential feedbacks is the key to understand such paradoxes. Consider another paradox of high unemployment in agriculture-dominated basins. One dominant theory is that regions with larger diversity in occupational choices often fare better in employment than regions with specialized economies such as those dominated by agriculture.[36] This is because diversified economies allow people to change their occupation under challenging economic environment. The exploration of potential feedbacks between economic environment (e.g., commodity prices) and employment opportunities (e.g., economic opportunities outside water-dependent agriculture sector) thus helps to explain the phenomenon.

In the case of coupled human–water infrastructure systems associated with urban flooding, raising the height of levees, for example, may lead to extremes never anticipated before, such as the exposure of the

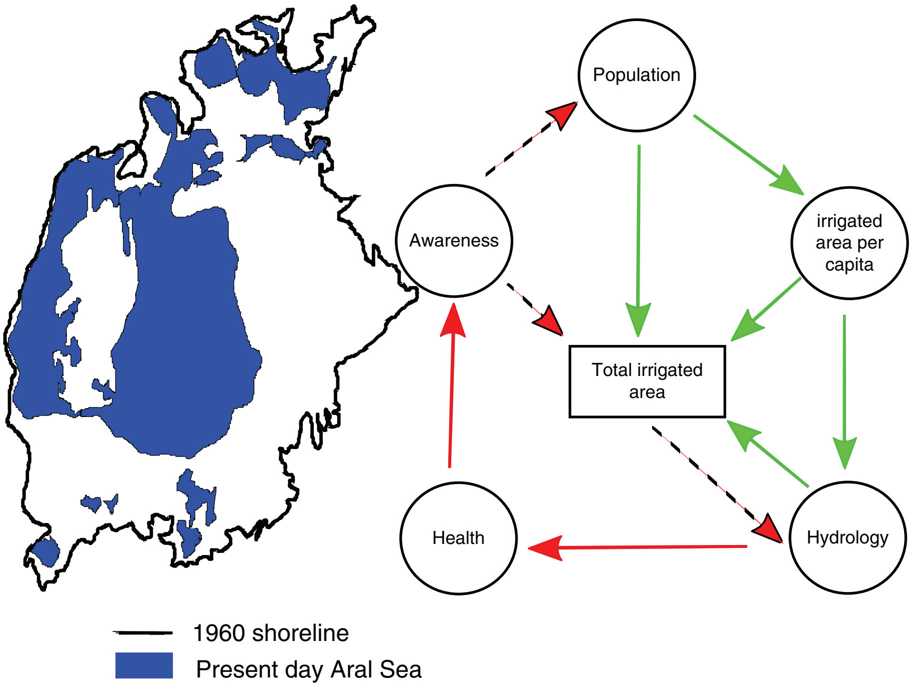

FIGURE 2 | Aral sea desiccation. Left panel, 1960 shoreline versus present (Source: http://earthobservatory.nasa.gov/Features/WorldOfChange/aral_sea.php?all=y) and right panel, a general framework coupling various possible elements of the dynamics. Green arrows indicate positive feedbacks, red arrows indicate negative feedbacks, and dashed red arrows indicate weak negative feedbacks, due to which drying out of Aral sea went without check. The collapse of the Aral sea may be attributed to weak institutions that could have otherwise inhibited the expansion of total irrigated area. This happened in spite of heightened concerns for environmental hazard (such as health concerns).[34]

population to rare but highly damaging flood events—often unknowingly exposing population centers close to the river system.[37] But the effect of raising levees can only be understood by exploring the system's 'possibility space,' i.e., by iterating between observed patterns of human settlements in the floodplains over time and the concepts that dynamically link various aspects of coupled human–water systems such as hydrology, memory of past floods, wealth, etc. This method of scientific inquiry generates new hypotheses about associated coupled human–water systems, predicts the phenomenon of interest, and then contrasts it with observations. The cycle of knowledge generation and update is continued until a satisfactory explanation of the socio-hydrological phenomenon is achieved.

METHOD OF SCIENTIFIC INQUIRY FOR SOCIO-HYDROLOGY

The method of scientific inquiry interprets emergent phenomena by means of the cyclic process of hypothesis generation, test of hypothesis through data analysis, and hypothesis update. In socio-hydrology, we begin by identifying variables such as water storage, population, crop production, salinity, capital that are possibly behind the phenomenon, for example, of the rise and decline of population in a water-scarce river basin. This is followed by formulating hypotheses on how these variables behave over time (e.g., variation in water storage is governed by water mass balance) and how these variables interact with each other (e.g., water abstracted from water storage is used for crop production that adds income to the capital equation, or population growth within a basin depends on how much food is available per person to consume). The behavior of the coupled system is then simulated by building on these hypotheses to generate diverse emergent phenomena under different initial and boundary conditions, e.g., rise and decline in crop production and population but with peak in population preceding the peak in crop production. If these generated patterns of crop production and population growth are corroborated by observed historical data then the proposed hypotheses, until they are falsified, are possible explanations of the observed phenomenon. If not, e.g., population

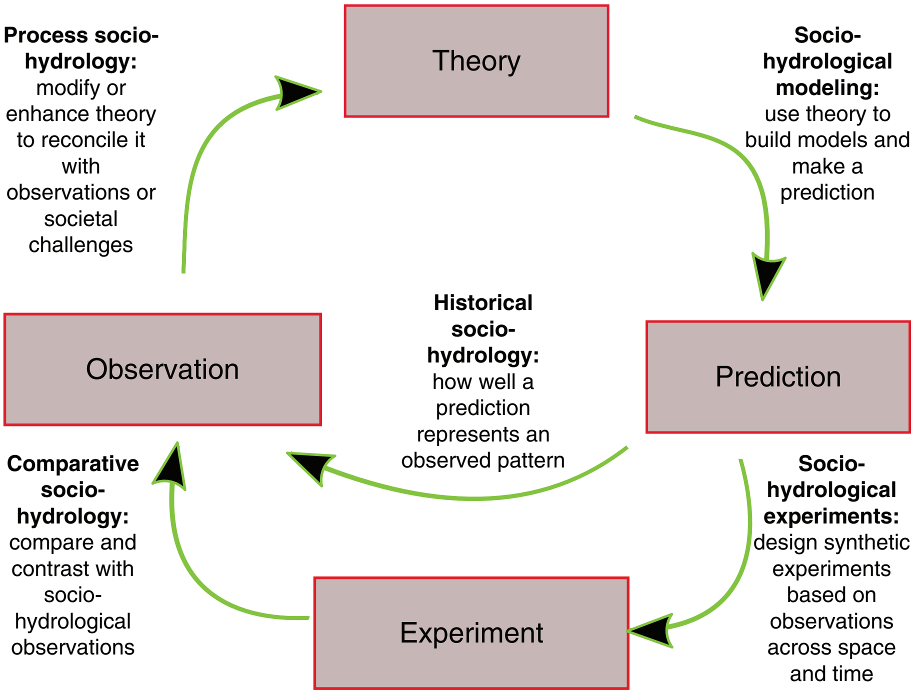

FIGURE 3 | The three subdisciplines of socio-hydrology and the method of scientific inquiry. This demonstrates that the standard method of scientific inquiry can be implemented to the diversity of coupled human–water systems using the three different but complementary pathways of socio-hydrology. (See Ref 40 for the three complementary pathways of socio-hydrology).

in fact continued to rise in spite of falling crop production, hypotheses about how the variables change in time or how they interact with each other are updated or new hypotheses are formulated, e.g., about the role of technology, and simulations are repeated until a satisfactory comparison with observed phenomenon is achieved.

The method of scientific inquiry to explore feedbacks in coupled human–water systems therefore requires (1) generation of knowledge of possible processes that contribute to the generation of observed phenomena and (2) historical or contemporary data that allows us to compare and contrast the performance of phenomena that can be simulated through model predictions. The feedbacks that are applicable for a given coupled human–water system can be selected by identifying gaps in our understanding of the system through the iterative process of hypothesis building→data evidence→hypothesis update.[26,38,39]

Figure 3 presents a generic framework for the implementation of the method of scientific inquiry to the diversity of coupled human–water systems[40,41] that we might encounter in the world. When the human–water systems are isolated systems (e.g., a river basin, flood control system in a city), and the socio-hydrologic phenomena of interest involve emergent patterns in the time domain, the pursuit of scientific inquiry can follow three different but complementary pathways:

1. Historical socio-hydrology: with the aim to understand a coupled system from its immediate or distant past, whichever applicable.
2. Comparative socio-hydrology: with the aim to compare and contrast different coupled human–water systems across socioeconomic, climatic, and other gradients.
3. Process socio-hydrology: with the aim to understand and hypothesize about the nature of observed social and hydrological processes that contribute to the dynamics of the coupled human–water system.

Process socio-hydrology allows us to build hypotheses about how different parts of the coupled human–water system may be dynamically interconnected. Historical socio-hydrology allows us to document an emergent phenomenon in a single location, hypothesize mechanisms through which it may have arisen, and confront these hypotheses with the patterns in the historical record. Comparative socio-hydrology allows us to study the same phenomenon comparatively across many locations (i.e., river basins), formulate broader hypotheses about the similarity and differences in the way the phenomenon manifests across gradients of hydroclimatic and socio-economic conditions, and test these hypotheses with the use of data drawn from diverse locations. Figure 3 demonstrates that hypotheses about a particular coupled system (i.e., process socio-hydrology) can be adapted or updated by reconciling them with historical (e.g., long time scales) and comparative socio-hydrology in an iterative manner.

In this sense, these three analysis pathways appear to be exhaustive, i.e., any understanding of socio-hydrology that excludes any of these elements may be incomplete. When cyclically iterated, over time, these three pathways of scientific inquiry will enable generation of a coherent body of knowledge that may explain a diversity of phenomena occurring under different socio-hydrological conditions in terms of common or similar mechanisms. This remains the long-term goal of socio-hydrology. For the present, we will document what has been learned from the diversity of studies about coupled human–water systems that have been completed over the past 4 years under the umbrellas of historical, comparative, and process socio-hydrology.

PROGRESS IN SOCIO-HYDROLOGY

There have been several commentaries on the originality of the concept behind socio-hydrology and clarifications of definitions involved[13,39,42–45] since the introduction of the field 4 years ago.[41] These activities have illustrated the meaning and usefulness of socio-hydrology for understanding coupled human–water systems and toward sustainable water management.[43,46]

Socio-hydrology finds similarity in disciplines such as hydrosociology,[8,42] socio-ecology,[24] anthropology,[17,20] classical and contemporary sociological theory,[22,23] and human geography[47] in its treatment of coupled human–water systems. It interprets diverse phenomena that arise from coupled human–water systems such as the rise and fall of past civilizations[16,48] and seeks general principles that may be behind the emergence of such phenomena independent of space and time. The interpretations and principles are not limited to one tradition. For example, the evolution of coupled human flood systems, in particular, how levee heights may evolve with population, has been conceptualized based on system dynamic models[37] and economic growth models.[49,50] This exemplifies socio-hydrology as a field that encourages diverse perspectives rooted in the method of scientific inquiry in interpreting the same phenomenon.

Historical, comparative, and process socio-hydrology are the three pillars that jointly enable the implementation of the method of scientific inquiry. Here, we present a summary of contributions along these three dimensions of socio-hydrological inquiry.

Historical Socio-Hydrology

Liu et al.[51] provided a long-term historical perspective on the socio-hydrological dynamics in ancient Tarim river basin, China, which was followed up by Liu et al.[52] who proposed a working model of the system dynamics in recent times. In a similar vein, Kandasamy et al.[31] analyzed historical socio-hydrological datasets of Murrumbidgee River Basin (MRB) and proposed broad patterns of its socio-hydrologic dynamics in terms of key variables. One of the key observations made was that technological innovation, including building up of reservoir capacity, facilitated the economic growth within the basin. This study was followed up by van Emmerik et al.,[53] who modeled emergent temporal dynamics documented earlier by Kandasamy et al. Both Liu et al.[51] and van Emmerik et al.[53] conceptualized the socio-hydrological system as composed of interacting hydrological, demographic, ecological, and economic subsystems. They demonstrated that in both Tarim and Murrumbidgee basins, simple conceptualizations can replicate the historical patterns of dominant system variables such as flow, population, vegetation, and irrigated area.

In a comparative historical study, Pande and Ertsen[16] argued that changing patterns of water resource availability may have been behind the rise and fall of the Indus valley (Harappan, South Asia) and Hohokam (North America) civilizations and that lack of water resource availability may even have led to basin-scale solidarity. For example, the Harappan civilization rose to maturity over a course of 500 years when both the summer monsoon and winter rainfall were weakening, implying increased coordination at basin level. Ertsen et al.[54] further argued that the actions of humans at fine time scales such as managing irrigation systems at daily scales may have played a crucial role in guiding coupled human–water system trajectories of ancient societies. Recently Kuil et al.[48] suggested that smoothing hydroclimatic variability through building of reservoirs might have helped Mayan civilization to sustain longer economic growth and higher population growth. Fernald et al.[55] provided an interesting framework to understand the socio-hydrological resilience of traditional irrigation communities in New Mexico by studying key hydrological, ecological, economic, and sociocultural dimensions and their interactions. Zlinszky and Timár[56] suggested that historical maps can be a means to document past trajectories of coupled human–water systems. Dermody et al.[57] analyzed the consequence of spatial variability in water resource availability on virtual water trade and the resilience of regional food supply in ancient Rome, and the possible links to the eventual collapse of the Roman Empire.

These studies sought historic patterns to support theories and models of coupled human–water systems and to help understand documented cases of socio-hydrologic resilience. Technological innovation, in particular smoothing hydroclimatic variability through building up of reservoir capacities and trade appear to enhance the resilience. They highlight that it was challenging to identify locations with appropriate datasets at decade to century time scales with which to discover phenomena and to generate and test plausible hypotheses about the mechanisms behind these phenomena.

Comparative Socio-Hydrology

Srinivasan et al.[58] compared and contrasted six descriptors of water stress across 22 coupled human–water system case studies, which provided insights into how improved water policies may be designed to reduce inequity, vulnerability, and unsustainability of freshwater use. Scott et al.[35] addressed the impacts of increased efficiency in water use and water savings on the resilience of socio-hydrological systems by studying three contemporary river basins. They showed that water 'saved' through irrigation technology improvements may lead to unintended consequences for water use at multiple scales and in multiple sectors. Konar and Caylor[59] analyzed the impact of spatial variability in water resource availability on virtual water flows and development in Africa.

These studies generated an understanding of resilience and sustainable water use by comparing and contrasting diverse coupled systems. Such studies, nonetheless, have been rare. This again underlines the challenge to identify datasets of, e.g., water infrastructure, water use, and population growth in diverse hydroclimatic and socioeconomic settings. A further challenge is to explain similarities and differences identified in these comparative assessments with bold hypotheses.

Process Socio-Hydrology

In a more contemporary setting, Srinivasan[60] modeled the socio-hydrology of an urban area in India where increased groundwater use is leading to reduced availability for future consumption. Di Baldassarre et al.[61] discussed the coupled nature, i.e., the two-way feedbacks, of humans and floods in flood prone societies (e.g., cities). Di Baldassarre et al.[37] introduced a parsimonious coupled set of differential equations representing dominant socio-hydrological variables such as economy, technology, and levee height to model the system dynamics of a flood prone society. Grames et al.[49] followed a more formal optimization-based approach to understand coupled human–flood systems. Chen et al.[32] conceptualized how a flood prone society in Kissimmee river basin moved from river channelization to restoration as a result of power play between upstream and downstream users. O'Connell and O'Donnell[62] investigated another important aspect of such a coupled system, i.e., how persistence in flood events may influence adaptation strategies of human societies from proactive to defensive, even if persistence does not affect the memory of a society.

Meanwhile, Robeiro Neto et al.[63] assessed the infrastructure vulnerability of the urbanizing Capibaribe River Basin under climate change. Zhang et al.[64] studied the impact of drip irrigation on regional groundwater dynamics in the Tarim river basin and the secondary salinization introduced by such anthropogenic activity. Gober and Wheater[65] argued that emerging challenges of the Saskatchewan river basin, such as series of extreme events, rapid population and economic growth, overallocation of resources, and outdated institutions to handle such challenges, are symptoms of a socio-hydrologic system that is approaching a critical threshold.

Konar et al.[66] suggested that spatiotemporal variability of water resource availability would potentially influence virtual water trade flows. Kummu et al.[67] studied the impact of interannual variability of water availability on food production potential at global scale. O'Bannon et al.[68] suggested that virtual water trade has led to a globalization of agricultural pollution. Shi et al.[69] studied the evolution of China's virtual water trade and found that it has been a net importer of virtual water from water-abundant areas and a net virtual water exporter to water-stressed areas of the world. Pande et al.[70] studied the effect of water scarcity on technology, agricultural production, and population growth within a basin. Inspired by historical and comparative assessment of selected socio-hydrological phenomena, these process-based studies have proposed a range of interdisciplinary theories and models of the positive and negative feedbacks between humans and the water environment.

WHAT HAS BEEN LEARNED: ENDOGENIZING HUMAN AGENCY

A critical inspection of the body of socio-hydrological knowledge that has been generated till now indicates that it has been influenced by a few selected phenomena. The modeling paradigms proposed in van Emmerik et al.,[53] Liu et al.,[51] and several others were inspired by the 'pendulum swing' phenomenon presented in Kandasamy et al.[31] and Liu et al.[52] Similarly, the models of Di Baldassarre et al.[61] and others on coupled human–flood systems were inspired by qualitative descriptions of behavior relating to population growth, levee rise, and flood occurrence in several locations. Both of these modeling approaches are in the form of a system of coupled differential equations that show an emphasis on system engineering and nonlinear dynamics. The modeling studies by Srinivasan,[60] Pande et al.,[70] and Grames et al.[49] were inspired by similar patterns of coupled human–agriculture and human–flood systems and based on the assumption that humans make rational choices in order to maximize their well-being. Both types of approaches explain phenomena by linking the capacity of humans to alter their water environment, i.e., human agency, to benefit humans and/or their environment, giving rise to the bidirectional feedbacks that underpin the emergent phenomena that we have been witness to in many circumstances.

Technology plays a crucial role in how human agency alters its water environment, e.g., how humans utilize water for their well-being. Examples include dams,[71] irrigation technology (sprinkler irrigation, drip irrigation etc.), and irrigation structures,[31,35,53,54,63] groundwater pumping,[60] levees against flooding,[37,61,62] plant breeding,[31] etc. It sustains wealth generation even under increasing population pressure and in this way helps to sustain positive population growth in spite of finite resources. However, there is a limit to how far technology can continue to underpin economic growth through resource exploitation. It may appear that technology-mediated society exploits land and water resources limitlessly but as more water and land is used, as population size increases, the risk of eventual societal dispersal or collapse increases.[16] For example, presence of levees may incentivize the population to settle in otherwise flood-prone areas only to be exposed to lower probability but more destructive floods.[37] Introduction of water saving technologies such as drip irrigation may cause increased dryland salinity,[31] and contribute to the so-called efficiency paradox of yet more land being irrigated instead of water being left to the environment, or the 'scale paradox' of reduced return flows downstream.[35]

It therefore remains unclear as to what extent technology can ensure a sustainable future. A conservative observation is that technology-driven economic growth leads to increased environmental hazard and degradation such as higher flood risk, reduced return flow downstream, and increased salinity in coastal areas. This negatively feeds back to human agency. A community may become sensitive to environmental degradation and may respond to changes brought about by its technology-driven pursuit of improved human well-being.[72] The values and norms of a society in respect of water resources and the environment may even change as a socio-hydrological system becomes more vulnerable, posing a threat to sustainable use of water and land resources for human well-being.[53,61,72] Unintended negative consequences may become part of the social consciousness, sensitizing communities to further degradation. The behavioral response of communities, e.g., in the form of environmental activism (i.e., green movement), then helps to translate changes in water and land use practices into political and legislative actions.

This competition between technology-mediated growth and environmental sensitivity endogenizes the human agency. The competition can be conceptualized as the interplay of positive (e.g., technology-driven use of water resource for enhancing human well-being in the short term) and negative (e.g., the impact of environmental degradation on future well-being, i.e., in the long term) feedbacks. What is interesting is that the timescales associated with the positive and the negative feedback loops often differ.[13] Positive feedbacks loops operate at monthly to annual time scales while negative feedbacks may take decades to a century to impact humans[31,53,70] .

It may not always be the case that the behavioral response is fast enough or strong enough to mitigate positive feedbacks of human agency. In some cases, the absence of institutions may inhibit negative feedbacks of communal sensitivity to degradation. For example, the basins that flow into the Aral Sea (in the former Soviet Union) witnessed intense population growth and water consumption for cotton production during the Soviet era. This led to reduced flows to the sea, to the extent that there was a rise in the cases of lung diseases and the fisheries industry

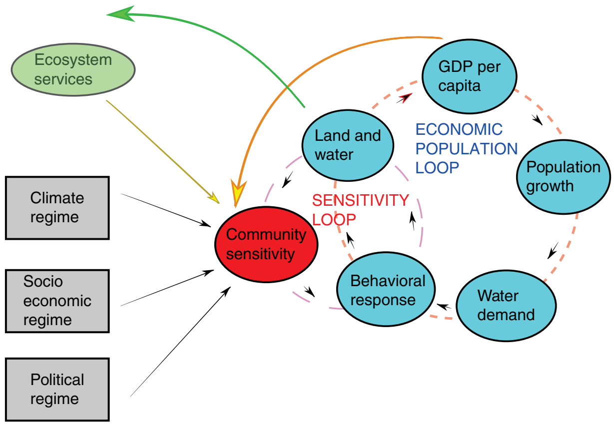

FIGURE 4 | Endogenous human agency and the role of institutions. Community sensitivity is critical in feeding back negative consequences of past actions on human agency of water and land use. Yet desirable remedial actions only take place if the link in the sensitivity loop between behavioral response and land and water use, which is institutional in nature, is strong. Contrast this with Figure 2 where the feedback from environmental awareness and human agency of irrigated agriculture is weak. (Reprinted with permission from Ref 72. Copyright 2014)

collapsed as the lake desiccated. As Figure 2 illustrates through weak feedback of awareness on total irrigated area, while the community was sensitive to environmental degradation, the central planners' directive to grow cotton in the desert may have overridden that.[34] Contrast this with MRB in Australia, where strong institutions emerged from the coevolution of the coupled human–nature system (e.g., green movement). They acted as a conduit for the environmental awareness in the community to be channeled through to eventual remedial action.[31] Figure 4 claims that community sensitivity is critical in this respect, yet desirable remedial actions only take place if the institutional link in the sensitivity loop between behavioral response and land and water use is strong. Bijker[73] made a case that this institutional link may develop in different manner even for two similar technologically advanced societies. This may be due to historical differences in attitude toward (flood) risk, leading to different paths of institutional development for the two societies.

Irrespective of how the two-way feedbacks between humans and their water environment are conceptualized, it is clear that new phenomena emerge when technology (e.g., infrastructure, water saving technology, and plant breeding), norms and values relating to water and the environment (e.g., environmental awareness, community sensitivity, and flood memory), institutions, and socioeconomic growth (e.g., agricultural production and population growth) are part of system dynamics. Often societal resilience is attributed to institutions and culture that emerge from and evolve with intrinsic dynamics of societies.[55,73] The understanding of two-way feedbacks also facilitates water management in part by endogenizing the scenarios (e.g., of future population growth[70] that influences resource use), which are a crucial input to water resource management and for rejecting unrealistic scenarios of unlimited population growth. The endogenization of human agency is therefore crucial if robust policy analysis is desired.

KNOWLEDGE GAPS AND UNRESOLVED CHALLENGES

Socio-hydrology as a science would naturally follow the method of scientific inquiry to generate understanding of observed phenomena. The method of scientific inquiry adopted also exemplifies the challenges that the field currently faces. These challenges are either those that inhibit the iterative process of learning or those that appear as a result of the iterative process of learning and knowledge generation.

The method of scientific inquiry may start with observations of a phenomenon first and then construct a set of hypotheses based on a given level of understanding. The reliability of such a construct depends on reliability of observations and how well predictions of the phenomenon can be tested against observations.[74] Hydrological modeling literature has plenty of examples of long datasets of multiple variables such as evaporation, streamflow, and water table depth being used to critically evaluate model simulations to reduce equifinality.[75] Observations of diverse variables such as evaporation have been motivated by the need to accurately model the underlying processes. Better measurement techniques also reduce parametric uncertainty. Socio-hydrology, being a new field, will be no different in its demands for historic datasets,[43] e.g., to reduce equifinality. Given the complexity of systems being studied, now involving human systems, it is quite challenging to collect data of sufficient length at relevant spatial scales.[76] Data on human systems, e.g., detailed socioeconomic surveys on crop production, labor availability, and use of water for productive purposes, are often expensive to collect and are not available at even annual time scales. The human agency in itself makes observations of human behavior, such as how we choose to consume, difficult to quantify and measure. Long historic data, e.g., on levee building or trade, are difficult to produce because such information has often been documented in historical narratives and not in formats that traditional hydrologists are used to.[37] They are also subject to interpretation of those who documented the records and those who might use it as input to understand socio-hydrological systems.[77]

The task of a phenomenon inspired socio-hydrologic theory to compile knowledge from relevant disciplines within a quantitative framework is not at all trivial. A quantitative framework is needed to interpret a phenomenon in a comparative setting. This would need some kind of metric or rationale to convincingly argue why one interpretation appears to be more suitable than another or how the scientist would go about improving his or her knowledge or interpretation of the phenomenon. Furthermore, variables that would be compared with observations to support such interpretations would need to identified and defined. Once possible relationships between such variables have been defined, a quantitative framework has been defined to interpret the phenomenon. In other words, a quantitative framework prescribes the variables that are to be measured, e.g., population, agricultural production, wetland storage etc., as well as the scale at which they need to be measured.

There are many opportunities to inspire cohesive, phenomenon-specific socio-hydrological theories and frameworks that build upon the knowledge of constituent fields.[76,78] But then again, many social processes such as the evolution of human values, norms, and institutions, which play a critical role in defining the societal feedbacks within the socio-hydrological framework,[40] may require concepts that are difficult to measure.[79] For example, what should be the units of measurement of a society or community's sensitivity to its wetlands (even while acknowledging that such a concept may not be agreeable to all normative social scientists). While fields such as economic theory have explored several such questions, e.g., how to measure the utility that humans derive from consuming goods such as food, and environmental services such as bird refuge or aquatic recreation, these efforts also foretell difficulties in validating interdisciplinary socio-hydrological models, since not all of the variables constituting these models may be measurable.[79] For example, it is unclear if agents protect their environment for their future generations and it is difficult to measure the extent to which humans are willing to go to protect their environment.

The generation of new hypotheses as part of the iterative process of scientific inquiry and knowledge discovery is challenging. The need to develop new concepts appear when explanations provided by current models or theories are unable to replicate observed patterns and interpret phenomena.[26,39] Abstract concepts such as the overlapping generation model and the economic growth model have been used to analyze socio-hydrological systems, such as the human–food and human–flood systems. These have been inspired by existing theories of endogenous growth[49,70] in an effort to augment the 'possibility space' that can be used to interpret the phenomenon of interest. Even then, such efforts may not provide a fully satisfactory explanation.

A related concern arises from the use-inspired nature of socio-hydrology[40]: approaches to studying coupled human–agriculture, human–flood, and human–urban systems are reflexive of the societal need to solve such problems and are bound by the biases of the researchers or the practitioners involved. Further scientific knowledge, like any other type of knowledge, is contingent on the specific cultural, political, economic, and technological circumstances within which it is produced, and in turn feeds back to the circumstances. This is often much more subtle than scientists simply choosing what to study. This argument has been made by van der Zaag,[80] Lane,[77] and Krueger et al.[25]

The body of knowledge that the field would generate would be biased by the paradoxes and patterns that it chose to study (such as the pendulum swing, the levee effect, etc) and by the momentum that it would carry from the concepts developed in the past (e.g., concepts such as endogenous growth[49,70] and system dynamics[28,37,53]). Thus one has to cautiously balance inclusiveness of diverse fields and the level to which various fields may contribute to the development of the field in the long run. This is akin to path dependencies and lock-in situations that are associated with the use of natural resource such as water[25] and coal.[81]

This calls for a cautious yet inclusive approach to explore more diverse phenomena and concepts than the relatively few that have been explored so far, so that a rich body of knowledge can be generated in course of time. The development of socio-hydrological theory can be fuelled by exploring bold hypotheses, e.g., by facilitating the method of scientific inquiry through identification of patterns in data[82] and using information theoretic approaches[83,84] to reveal underlying causality and inspire hypotheses (data→patterns→information flow→hypothesis generation→hypothesis testing). This could break the dependence of socio-hydrology on the limited number of phenomena that it has studied till now.

The distinguishing feature of socio-hydrology is the treatment of humans as endogenous to the system with implications for robust water management, e.g., by rejecting unrealistic scenarios of population growth, economic growth, technological development, and water use. However, at present, all socio-hydrological models that are presented in the literature are low dimensional and focussed on modeling temporal dynamics. This poses the challenge of how to increase the complexity of such models in a manner that not only replicates dominant patterns of coupled human–water systems but also are valuable to management and policy in a highly connected world.

FUTURE CHALLENGES: SPATIAL DIMENSION OF SOCIO-HYDROLOGY

Socio-hydrological development has so far mostly focused on dynamics of coupled human–water systems in the time domain. Exceptions include contributions to virtual water trade. Such analyses of socio-hydrological systems assume that systems are isolated entities in space, such as the farm plot of a marginal farmer, and that the effect of these entities outside its system boundaries can be summarized by its boundary conditions. However, socio-hydrological entities such as small-scale farmers, basins, or countries are interconnected in today's highly connected world. The space-time linkages are not only at each scale but also across scales and can lead to emergence of diverse phenomena such as large-scale droughts.[85] Trade networks spread knowledge, and can bring in sudden changes in land use policies such as rapid deforestation in the Amazon or even changes in how resources are governed. The understanding of dynamic patterns of interconnectedness through trade and the global hydrological cycle is therefore critical to the assessment of long-term water resource availability at global and local scales.[86] This demands an extension of systems with endogenous human agency to space and to space-time.

A natural extension is therefore to endogenize the boundary conditions themselves, e.g., of trade or rainfall, just as socio-hydrology has endogenized scenarios in the time domain, e.g., of population growth, through bidirectional feedbacks. This requires us to understand additional processes that connect socio-hydrological entities in space. For example, two sub-basins have their internal socio-hydrological dynamics of population, and water-food-energy nexus, but can be interconnected by streamflow. Similarly, socio-hydrological processes of basins that are not directly hydrologically connected may be linked by trade in goods that agents in both the basins consume or by atmospheric fluxes, i.e., evaporation from one basin falling as rainfall in a downwind basin.

What should be the limits of such extensions? The spatial linkages can be introduced as long as system boundaries remain open. In the context of socio-hydrology, a system is open if there are fluxes that flow across system boundaries. Examples of these fluxes include physical liquid water in terms of upstream to downstream flows, vapor to liquid water fluxes in terms of atmospheric moisture cycling,[5] virtual water embedded in traded commodities,[87] or even capital, technology, or knowledge that affect local socio-hydrological processes. An appropriate upper limit is the planetary scale,[88] the scale at which the fluxes that cross planetary boundary do not influence socio-hydrological processes within. The extension then requires the smallest scale, e.g., plot scale relevant for marginal farmers, and increments in scales, e.g., plot→basin→country→planetary, upon which the knowledge of spatial hydrology could be built (see e.g., Ref 89). This can be based on what we have learned so far from the practice of socio-hydrology.

Basin-scale socio-hydrology has been widely understood as socio-hydrological units (such as sub-basins) interconnected by water flows. Diverse basins or administrative units to which the basins belong to are interconnected by trade. The basins are also interconnected by atmospheric moisture with evaporation in one basin appearing as rainfall in a downwind basin, quite similar to sub-basins interconnected by river flow in the downstream direction.[5] Such a hierarchical understanding of nested scales starts at sub-basin or pixel scale and ends at the planetary scale. For example, changing land cover patterns upwind may influence the intensity or the amount of rain that feed into a basin[5] and affect the amount of food crops that it can produce and export.[66] This in turn influences virtual water flows that feed outwards to other countries affecting national economies and effecting changes in land use policies, triggering a cascade of feedbacks from local to global scale.

This presents an opportunity to assess sustainability of global water use for humanity, e.g., by strengthening our understanding of planetary water boundaries in a bottom-up manner based on local environmental flow demands.[90,91] Kates[47] was one of the first to propose a conceptualization of the hydrological cycle in terms of various subsystems through which the water 'physically' flows. This perspective further appeared with subsystems described in greater detail in Falkenmark,[92] who proposed a framework in the context of sustainable water use

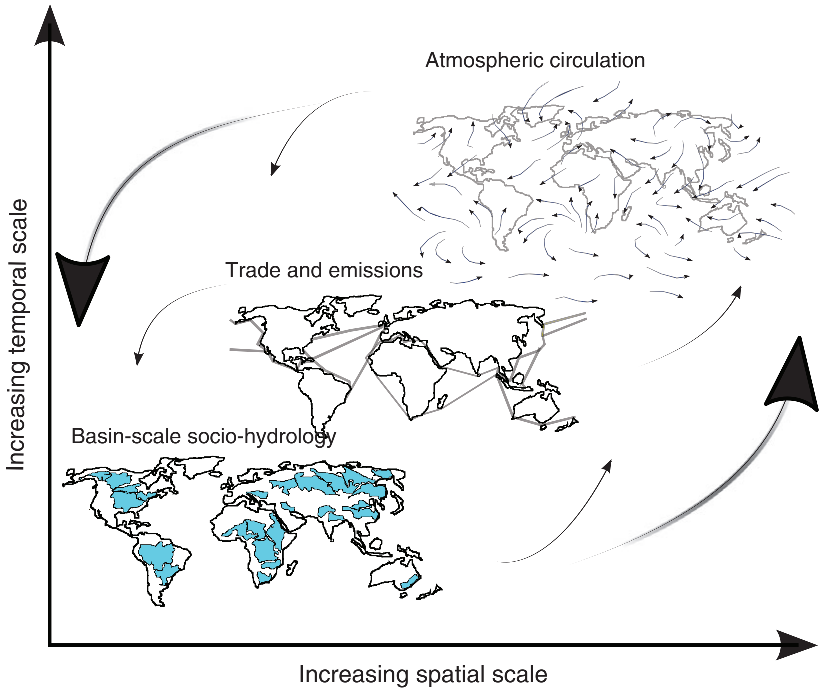

FIGURE 5 | Notion of interlinked socio-hydrological systems at multiple space and time scales. Three socio-hydrological systems are considered at different spatiotemporal scales. Basin-scale socio-hydrology prevails at finest spatiotemporal scales, followed by trade and associated economic activities that occur at regional scale with patterns of trade evolving at decadal scale. These kinds of socio-hydrologies may influence the hydrological cycle at planetary scale. The arrows indicate the feedbacks between various scales.

and development. These are two of the earliest examples, which interpreted the hydrological cycle as human subsystem physically coupled to the water cycle. Liu et al.[93] has similarly been arguing for a hierarchical integration of relevant subsystems at finer spatial and temporal resolutions to address global sustainability challenges that we face, such as safe operating space for humanity in terms of resource use. Such efforts have led to the emergence of the notion of tele-coupling in Land System Science (LSS),[94] where location-specific land cover dynamics is influenced not just by local drivers of change such as population pressure but also distal coupled social environmental/land cover dynamics through flows such as trade of goods and of knowledge.

Similar efforts are also being undertaken by the Integrated Assessment Modeling (IAM) community. A prime example is the Platform for Regional Integrated Modeling and Analysis (PRIMA)[95] modeling framework that models the dynamics of supply and demand of various economic goods in various regions of the world. It explicitly identifies and models the feedbacks between water, land, climate, energy and economy, and integrates variables such as streamflow at daily and basin scale, and economic variables at annual scale to climate change effects at decadal scales. However, this it does at extremely high modeling and computational costs.

Socio-hydrology with an accompanying top-down modeling approach[96] can strike a balance between model complexity and realism. Kates[47] similarly argued that even basic knowledge of some general principles can go a long way explaining 'what is found where on earth' in her call to relate physical to human geography. Socio-hydrology offers a constructive framework to model and simulate planetary boundary variables at the global scale that are linked to and connected by water (physical or virtual). One may envisage such a spatial socio-hydrological framework as a collection of basin-scale socio-hydrologies that are teleconnected not just by atmospheric circulation patterns but also by (endogenously evolving) networks of trade. Consider Figure 5 for example. Next to water and trade teleconnections, there are (sometimes contested) teleconnections of (global scientific and local lay) knowledge and (localizing to globalizing) value systems.[97] The effect of global economy to national, basin, and even sub-basin farm scale local economies can be cascaded through this scale-rich network of global and domestic trade networks and vice versa. For example, a shock in global rice prices can be cascaded down to local socio-hydrological systems, while the effect of local land use practices, water use, or production technology at diverse temporal scales can be upscaled to other socio-hydrological basins through atmospheric and economic teleconnections. Spatiotemporal socio-hydrological models may then be seen as parsimonious versions of IAMs.

The value of such a multi-scale approach to spatial hydrology is clear. Similar in spirit to Falkenmark,[92] it proposes a framework to decompose emergent global-scale phenomena, such as large-scale droughts or planetary-scale water scarcity into local causes and effects, enrich our understanding of such phenomena and help design robust hydrological or financial instruments for sustainable development.

CONCLUSION

It has been 4 years since the nascent field of socio-hydrology was launched. There has been considerable activity in the last 4 years under the umbrella of socio-hydrology. This paper restated the case for socio-hydrology by articulating the need to consider the two-way feedbacks between human and water systems in order to interpret and understand puzzles, paradoxes, and unintended consequences that arise in the context of management of human–water systems. This feature distinguishes socio-hydrology from other related disciplines such as hydrosociology and hydroeconomics, which also explicitly study human–water systems and positions it alongside fields such as anthropology, sociology, and hydrology. The paper then presented a critical review of past research on socio-hydrology through the prism of historical, comparative, and process socio-hydrology, documenting both the progress made and the challenges faced, both conceptual and operational. Barring the exception of virtual water trade, much of the work done so far has involved studies of socio-hydrological systems in spatially isolated domains (e.g., river basins), and phenomena involving emergent patterns in the time domain. The modeling studies then involved testing hypotheses about how these temporal patterns emerged.

An important feature that these studies have brought out, and which distinguishes socio-hydrology from other related fields, is the importance of allowing human agency (e.g., socioeconomics, technology, norms, and values) to be endogenous to the systems. Although the field is in its infancy and these conclusions are preliminary, these provide a focal point and key motivation for hydrologists and social scientists to come together and through a combination of coordinated field studies, retrospective analysis of past coupled human–water behavior and modeling studies, and develop new theories that allow generalization beyond individual places.

The meta-analysis also highlighted the fact that so far only a few emergent phenomena have been explored, and that a rich diversity of phenomena will be needed to advance the field. In this context, the paper articulated the need to extend socio-hydrology to the space domain, through discovering and exploring phenomena in space and in space-time. This becomes crucial as the world becomes increasingly globalized, and human–water systems are no longer isolated, but are highly interconnected at a hierarchy of scales, through upstream–downstream and upwind–downwind connections, interbasin transfers of real water, and interbasin, inter-regional and international transfer of virtual water through commodity trade. The endogenization of human agency, in terms of values and norms, technology, economics and trade, and environmental degradation must also be extended to space and space-time. This is a necessity for global water sustainability, but poses enormous challenges to socio-hydrology.

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