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Sociohydrology, ecohydrology, and the space-time dynamics of human-altered catchments

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Abstract A variety of interdisciplinary fields have provided distinct and complementary perspectives on human-water systems over the past few decades. In that context, an important distinctive feature of sociohydrology is its historical and methodological link to ecohydrology. This linkage implies a compatibility between the two fields that can be leveraged to address important modelling challenges in both fields. Sociohydrology has thus far focused on temporal dynamics and can benefit from recent advances in ecohydrology to represent spatial dynamics in coupled human-water systems. Conversely, as it increasingly focuses on human-altered catchments, ecohydrology can benefit from sociohydrology in terms of developing models of human behavior that are compatible with (eco)hydrological models, while consistent with prevailing social science theories. We review recent work in ecohydrology and sociohydrology that substantiate these two arguments, and discuss the modelling of water-borne diseases as an example of a promising avenue of research that connects the two fields.

Keywords: Space-time dynamics, ecohydrology, models of human decision, economics, sociohydrology, epidemiology

1. Introduction

Understanding the dynamic and tightly coupled relationships between humans and water has been an important focus of transdisciplinary research for decades (see e.g., Vogel et al., 2015). Interdisciplinary research initiatives rooted in engineering, policy and the environmental and social sciences have all added a unique perspective on a complex and multifaceted issue. As one such initiative rooted in the hydrology community, sociohydrology has gained substantial momentum over the last decade (Figure 1). The initiative has generated a renewed focus on coupled human-water interactions, both within hydrology and beyond, and a non-negligible share of authors of recent self-identified sociohydrology papers do not have a hydrology background (Figure 1).

Despite its rapid growth, sociohydrology has landed on an already crowded field. Some have questioned the novelty of the questions asked and methods used, thus fueling an ongoing debate on what sociohydrology is and how (or whether) it is distinguishable from other research initiatives focused on coupled human-water systems (Sivakumar 2012, Madani and Shafiee-Jood, 2020). We suggest that an important distinctive feature of sociohydrology is its historical and methodological link to ecohydrology (in line with Sivapalan 2018). Much like humans, plant and animal organisms can adapt to, and ultimately affect, prevailing water balance dynamics. They can do so not only by adjusting their own characteristics, but also by modifying the environment around them (Gao 2014, Troch et al., 2009; Yang et al., 2016; Brantley et al., 2017). This recognition has underpinned the development of ecohydrology which combines hydrologic principles with modern ecology within a unified modeling framework that has shed new light on the relationship between water and the biota. Although originally focused on the integrated study of ecological and hydrological processes in wetlands (Ingram, 1987; Zalewski et al., 1997), ecohydrology was later extended to terrestrial ecosystems (Rodriguez-Itrurbe, 2000; D'Odorico et al., 2010) and to the relationships between freshwater flows and ecosystem services (Gordon and Folke, 2000).

Further developing these approaches from ecohydrology to consider the relationship between water and *people* has been a major proposition of sociohydrology (Sivapalan et al., 2012; Sivapalan, 2018). Indeed, sociohydrology and ecohydrology ask similar types of questions, consider similar temporal and spatial scales, and use similar basic methodologies. Indeed, while ecohydrology explores the co-evolution and self-organization of flora and fauna in relation to water availability (Porporato and Rodriguez-Iturbe, 2013; Rinaldo et al., 2020), sociohydrology aims to understand the self-organization of human societies in relation to water, and the dynamic co-evolution of social and hydrological systems. This perspective illuminates an important new facet of coupled human-water systems that complements, rather than repeats, previous efforts in studying coupled human-water systems dynamics. Our goal is to review key advances in both sociohydrology and ecohydrology almost a decade after their branching out from hydrology. In doing so, our purpose is to highlight both the methodological compatibility of the two fields and their complementarity, whereby recent advances in each field can be leveraged to answer important open questions in the other.

Sociohydrology can benefit from ecohydrologic approaches to handling spatial dynamics and network connectivity. Representing the interaction between hydrologic flows and ecological connectivity throughout the landscape has been a major recent focus of ecohydrology. Ecohydrologic connectivity, and the associated spatial processes, have fundamental implications for the transport of nutrients and sediments, and the spread of species, populations, and pathogens (Mari et al., 2011). Just as ecohydrology aims to learn from species patterns and distributions, sociohydrology can potentially learn from human settlement patterns, by interpreting them in terms of access and proximity to water resources and socio-economic and technological factors (Sivapalan et al., 2012). Indeed, access to water resources has historically favored the development of human settlements along river networks, where those networks are used as a means of transport and water supply (Ammerman and Cavalli-Sforza, 2014). In the same way that altering flow regimes may change species community composition in riparian ecosystems, similar effects are also expected in human communities. However, sociohydrology so far has mostly focused on the time domain, seeking to elucidate the human-water feedback through time at a given location (Pande and Sivapalan, 2017; Sivapalan and Blöschl 2015; Rusca and Di Baldassare 2019). Most sociohydrological models incorporate upstream - downstream relationships, but the simplifying nature of many of these models in the way that they handle space and connectivity is ill-suited to represent the complexity of spatial patterns of human water interactions. In Section 2, we review two paradigms of ecohydrologic connectivity --

meta-community models and complex networks -- that are particularly propitious to, and indeed have been applied to, water-related human connectivity. We discuss these applications and their potential to both enhance, and be enhanced by, recent progress in sociohydrology in terms of representing water-related human decisions.

Conversely, by seeking to establish an interdisciplinary link between hydrology and the social sciences, sociohydrology can make important contributions to our understanding of the ecohydrology of human-altered catchments. Few of today's catchments remain unaltered by human development. Ecohydrology has developed rapidly in the past two decades in response to watershed ecological degradation and environmental changes worldwide, and is central to our understanding and quantification of water-related ecosystem services (Brauman et al., 2007; Sun et al., 2017). For instance, ecohydrological frameworks have been developed to evaluate the effect of flow regime alterations on species distribution and persistence in watersheds (Muneepeerakul et al., 2008, Lazzaro et al., 2017), and to the spread of invasive species and waterborne diseases (Bertuzzo et al., 2011; Rinaldo et al., 2020). Most recently, ecohydrological science has emerged as an important scientific field to address human influences on water resources and ecosystems under environmental changes ranging from urbanization to climate change (Gordon and Folke, 2000, Jackson et al. 2009).

In the emerging Anthropocene, humans are no longer mere external drivers or boundary conditions in ecohydrologic systems. Rather, humans are dynamically related to both water and ecosystems. However, the way people interact with water and ecosystems is fundamentally different from the way plants and animals do. This requires a different approach than traditionally used by ecohydrologists to model ecosystem responses. An approach that involves not only physical and biological processes, but a complex set of mechanisms. These mechanisms influence human response to hydrologic drivers, both at the individual and collective levels (Sivapalan et al., 2014). These mechanisms are described differently in different disciplines of the social sciences and, consequently, have been incorporated into sociohydrologic models using various approaches. We review some of these approaches in Section 3, focusing on their compatibility with ecohydrological models of water-ecosystem interactions. The purpose of this section is to outline the potential for sociohydrology to be leveraged to incorporate human interactions into ecohydrological models.

Section 4 discusses waterborne disease, both as an illustration of the symbiotic relationship between modelling advances in sociohydrology and ecohydrology, and to illustrate low hanging fruit for both approaches to be combined to address an urgent societal need. Finally, Section 5 concludes with some thoughts on whether and how ecohydrology can be leveraged to develop a (still lacking) theoretical framework for sociohydrology.

2. Modelling Spatial dynamics

2. 1. Community Ecology

Community ecology as a field is concerned with explaining the patterns of distribution, abundance and interaction of species. Such patterns occur at different spatial scales and can vary with the time and the size of the domain of observation, thus suggesting that different principles might apply at different scales (e.g., Levin, 1992; Rosenzweig, 1995; Maurer, 1999). Species are rarely distributed continuously in space but rather organized in local populations. Evidence from observational studies (Lomolino, 2001; Muneepeerakul et al., 2008; Mari et al., 2011) indicate that the distribution of species' persistence at observation sites are sometimes controlled more by the nature of the landscape where interactions occur, than by features specific to the underlying ecosystem (Bertuzzo et al., 2011). For example, dryland vegetation is known for its ability to exhibit a high degree of spatial organization with well-defined patterns of vegetated and non-vegetated soil patches: these patterns essentially follow the gradient in precipitation and soil moisture ("noise-induced stability") especially in conditions of scarce water availability (Rodriguez-Iturbe and Porporato, 2004; D'Odorico et al., 2006). In a similar way, human communities are not randomly distributed in space, but often exhibit well-known spatial patterns that relate to the nature of the landscape or its resources (Fang et al., 2018). For example, cities are classic examples of fractals in that their form reflects a statistical self-similarity of hierarchy and clustering (Batty, 2008) that mirrors those of ecohydrological systems.

With regards to modeling, the emergent spatial pattern in community ecology lends itself to the extension of the classic concept of metapopulation, defined as assemblage of local populations of the same species linked by dispersal, to metacommunity models, which include the structure and dynamics of multi-species assemblages (Leibold et al., 2004). Levins' (1969) classical metapopulation model of extinction and colonization in an infinite number of equally connected habitat patches has since been extended to include spatially explicit colonization (Bascompte and Solè, 1996), relationships between the connectivity and heterogeneity of patches (Hanski, 1994), rescue from extinction via continued immigration (Brown and Kodric-Brown, 1977), destruction or creation of habitat patches (Verheyen et al., 2004), and presence of multiple species (Leibold et al., 2004). The main result of this structured metacommunity model is that landscape structure (e.g., savanna vs river network) and dispersal anisotropy affect decisively any measure of biodiversity (i.e., species richness) (Rinaldo et al., 2020). Biological dispersal is also a key driver of many fundamental processes in nature. Invasion (e.g., by a non-native species) controls the distribution of species within an ecosystem and critically affects their coexistence. In fact, the spread of organisms along ecological corridors governs not only the dynamics of invasive species, but also the spread of pathogens and the shift in species range due to climate or environmental changes (Rinaldo et al., 2020). For example, amphibian survival is influenced by both wetland habitat and their connections to other wetlands (Gibbs, 1993; Dudgeon et al., 2005). Because amphibians often persist in landscapes where wetlands are highly dynamic and fluctuate considerably in their inundation pattern, preserving the connectivity among these habitat patches is fundamental to population viability (Semlitsch, 2000; Allen et al., 2020).

Human movements are obviously much different from amphibians' and have been a focus of a diverse community of social scientists for decades (e.g., McNeill 1984, Black et al. 2011). On a fundamental level, however, human migration might be a comparable adaptive strategy for humans to navigate hardship and pursue a better quality of life. For example, three main determinants are thought to play a role in determining the destination of international migrants

(Table 1, Row 1): (i) the net benefits or improvements offered in a destination country, (ii) distance to that country, and (iii) barriers governing immigration into that country (Perch-Nielsen et al., 2008). These drivers are reminiscent of ecohydrological models (Table 1, Row 2) where species tend to (i) maximize their fitness through movement, but have their movement impaired by (ii) spatial distance and (iii) barriers to migration. In this view, species dispersal models might be leveraged by sociohydrologists as a basis to model human migration.

The future of ecohydrology also promises to inform understanding of the complex interactions of the biosphere and hydrosphere with the “anthroposphere”. Human history is affected by the need to control vital water resources (Butzer 2012). Historically, humans have followed river networks during early migrations (Bertuzzo et al., 2007) and have preferentially built villages close to rivers for navigation, water supply, and trade (Ceola et al., 2015; Fang et al., 2018). In addition to affecting human migration patterns, the structure of river networks also affects species migration and therefore patterns of aquatic biodiversity. Using a neutral metacommunity model, Muneepeerakul et al., (2008) showed that local species richness along the Mississippi-Missouri River System significantly increased in the downstream direction. The overall downstream increase in richness resulted from the converging character of the river network and the dry-wet climatic gradient. Incorporation of the complex mosaic structure of real landscapes into metapopulation and metacommunity models has been viewed as the main promise of landscape ecology. Sociohydrologists can leverage and extend metapopulation and metacommunity frameworks as a starting point to model the relationship between river networks and human migration.

The above review points to two ecohydrological paradigms that we think are helpful for sociohydrologists to consider when modeling human migration: (1) landscapes are heterogeneous mosaics of habitats and land uses, such that habitat quality varies across space; (2) landscape connectivity, which emerges as water and individuals of different species move across the landscape and interact, is important for population dynamics. Both paradigms connect the distribution and movement of water across the landscape with the distribution and movement of plant, animal -- and presumably also human -- populations. Below are specific examples of how these paradigms are operationalized in ecohydrological models, which we believe are useful for sociohydrologists to consider as they think about modeling the spatial dynamics of human populations.

First, incorporating landscape heterogeneity into models is important. Muneepeerakul et al., (2008) reproduced habitat heterogeneity by endowing fish habitat communities with a carrying capacity that depends on spatial location (specifically, total contributing catchment area as a proxy for fluvial habitat size). The variability in “habitat patch” areas is another typical metric used to reproduce landscape heterogeneity (Rybicki and Hanski, 2013). A habitat patch is a discrete area used by species for breeding or obtaining other resources. Therefore, larger patches could potentially host a larger number of species due to their greater resource abundance. Giezendanner et al., (2019) considered landscape heterogeneity by accounting for the difference in topographic elevation between habitat patches, since several species tend to occupy sites along elevation gradients (Dullinger et al., 2012). Second, a spatially explicit metapopulation model requires specific rules for species dispersal across a heterogeneous landscape. For example, Stochastic Patch Occupancy Models, SPOM, (Hanski, 1994; Molianen, 1999) compute the distribution of occupied patches, by considering focal species traits (extinction, colonization, dispersal distance) and patch spatial organization (patch gap distances). Neutral models (Hubbell, 2001) represent another valuable tool for representing species dispersal. The structured neutral model prescribes that at each time step, an individual, randomly selected from all the individuals in the system, dies. The dead individual's empty space is then occupied by a new species based on its dispersal kernel (function of the river network structure) and the habitat capacity. Once dispersed, species affect the properties of their new habitat and, in doing so, affect the heterogeneity of the landscape. This suggests a system where landscapes are fully coupled with the communities that they support, which is a hallmark of metacommunity models. Theory suggests that if the rate of patch change exceeds colonization, occupancy will decline, possibly resulting in population extinction (Van Schmidt et al., 2019). Land-use change can also interact with other aspects of global change, such as climate change and emerging diseases (Wolfe et al. 2005, Brook et al. 2008, Hof et al. 2011, Altizer et al. 2013). Thus, understanding the dynamics of metapopulations in human-altered landscapes requires integrating community ecology with both biophysical and social sciences to assess the behaviors of key actors that drive change in landscape structure in these coupled human and natural systems (CHANS).

2.2. Complex Networks

By focusing on the topological features of connectivity, complex network theory represents an alternative approach to study the spatial dynamics of humans and water. A substantial volume of work (much of it by ecohydrologists) has focused on the analysis of virtual water trade networks (Tamea et al., 2014; Fracasso, 2014, Sartori et al., 2017; Carr et al., 2012 amongst many others) . The import of food commodities can be represented as a virtual transfer of freshwater resources from production to consumption areas (Hoekstra and Chapagain, 2011). The network representation of the global trade system is a graph with a finite number of nodes (countries), connected by links that represent bilateral (virtual water) flows. These flows are often predicted using gravity trade models, which relate trade flows to the product of the ‘mass’ of the trading countries (often represented as their Gross Domestic Product -- GDP), their geographical distance and other possible factors characterising the trading partners (Tamea et al., 2014; Fracasso, 2014).

Despite their attractiveness, gravity models poorly capture three important characteristics of the water trade network: communities, intermittency and feedback. Regarding communities, Konar et al., (2011) found that clusters of countries that preferentially trade with each other tend to emerge and become key topological characteristics of the food trade network. This property can be captured by a fitness network building algorithm, where connections are more likely to emerge if associated with a stronger increase in a “fitness” value, here a function of the gross domestic product and average rainfall of the connected nodes. Sartori et al., (2017) combined a similar fitness algorithm (to construct the network) with a gravity model (to estimate individual trade volumes) to predict future water stress in individual countries under different climate scenarios. While promising, all above frameworks are missing a mechanistic representation of human decision: the different networks are set to evolve so as to optimize a particular network-scale metric (e.g., entropy, efficiency) rather than integrating human behavioral models. As such, they fail to incorporate the feedbacks between landscape heterogeneity (e.g., each country's virtual water endowment) and connectivity (e.g., virtual water trade volume) that are central to metacommunity models.

In an attempt to incorporate these feedbacks, Tu et al., (2019) proposed a multidimensional predator-prey system with preys (food resource pool) harvested by multiple predators connected through a network of interactions (trade). Their approach highlights the impact of the structure of the network of socio-environmental interactions on the resilience of the global food/resource-user dynamics. Interestingly, an increase in connectivity (an indicator of globalization) is associated with a decrease in resilience. Thus, without reshaping trade patterns, the intensification of trade links is expected to result in further resilience loss. The integration of human decisions in complex network approaches has also been used to assess patterns of human migration. In their model of displacement associated with sea level rise, Davis et al., (2018) account for the propensity of humans to move toward the region with the best opportunities. They use a so-called radiation model, where a probability density function (pdf) is associated to each node, i.e., variable, of a network and represents its attractiveness (e.g., the distribution of its wages). The number of opportunities at each node (e.g., job opening, itself possibly a function of migration) is then represented as the number of instances drawn from each pdf. Based on their draw, the agent then picks the node with the highest attractiveness that is closest to her origin. This model was applied to a situation, where environmental conditions render a place uninhabitable over a fairly short time frame. The core assumption is that, once forced to leave, the (static) attractiveness of potential destination nodes determines where migrants decide to go. This assumption is less valid for other types of migration, where the decision of where to migrate (or indeed the decision *not* to migrate) can be dynamic and affected by a variety of social and psychological drivers, including the social network of the migrant and/or their emotional attachment to their origin location. In that regard, replicator dynamics and prospect theory (briefly reviewed in Section 3.3) are promising avenues to incorporate these two specific drivers of migration within a sociohydrological framework.

A key advantage of complex network approaches is their ability to elucidate the relationship between spatial connectivity and human-water interactions using a finite set of network metrics that contain important information about the structure, the efficiency, and the resilience of the system. For example, node degree is a basic metric that represents the number of links that are incident to a given node. Nodes with high degree (i.e. hubs) are highly connected to other nodes and their removal could potentially fragment the entire network, thereby limiting the flow (e.g., of species, information or goods) among the remaining nodes. The tolerance of a network to removal of these hubs is extremely low for scale-free networks (networks whose degree distribution follows a power-law; Albert et al., 2000); scale-free networks are otherwise robust to the removal of low degree nodes. However, from an epidemiological perspective, for example, the targeted isolation of these nodes (e.g., via a vaccination campaign) in highly connected networks can prevent the spreading of disease across the entire system of communities. Node betweenness is another important metric for characterizing the local properties of networks, and is defined as the fraction of shortest paths going through a given node (Estrada et al., 2009). It can be regarded as a measure of the “importance” of a node as a controller of the information flowing between other nodes in the network. Thus, nodes with high betweenness, the so-called “stepping stones”, are extremely valuable because they are critical for maintaining connectivity.

Assessing the values of these local metrics (e.g., node degree and betweenness) is important from a landscape management perspective because it makes it possible to rank and prioritize the conservation and protection of certain habitat patches. Similarly, such metrics might enable the identification of vulnerabilities in coupled human-water networks, including global trade. In addition to local information, other network metrics can provide information at the entire domain scale. For example, computing the clustering coefficient of the network can show which nodes in the graph tend to cluster together. Fortuna et al. (2006) used this topological metric to quantify the chance of amphibians moving from unsuitable (dry) to favorable (flooded) ponds. In a similar way, network modularity measures the strength of division of a network into modules. Networks with high modularity have dense connections between the nodes within modules but sparse connections between nodes in different modules. For example, Tu et al., (2019) used node modularity to investigate the resilience of the food trade network, concluding that the decrease in network modularity may promote critical transition in the system since local perturbation can more easily spread through the system.

3. Modelling Human Systems

3.1. Challenge 1: Cross Disciplinary Integration

A fundamental challenge in hydrology has been (and continues to be) to reconcile the highly diverse aggregate behavior of basins (e.g., the variability of streamflow measured at its outlet), with the universal laws of physics that govern water movements at the disaggregate scale. Short of a general theory to reconcile hydrologic observations across scales, recent research in hydrology has revolved around the study of phenomena, and the development of dedicated models to represent them (Sivapalan, 2018). By phenomenon, we mean a consistently observed system behavior that is consistent with fundamental theory but not directly derived from first principles. Well-known examples of phenomenological models in hydrology include first-order linear differential equations (e.g., the linear reservoir model) used to describe groundwater contribution to baseflow, or the Fickian diffusion used to model transient flow in porous media (Sivapalan, 2018). Phenomenological models are also prevalent across the natural sciences, including ecology where first order linear differential equations (exponential growth) and Fickian diffusion have been used to respectively represent population growth and species dispersal (Sibly and Hone, 2002; Cohen and Murray, 1981). The methodological compatibility between hydrology and ecology that this suggests has facilitated the development of ecohydrology as a modeling science.

Similar to hydrology, and for similar reasons, sociohydrology has also focused on the identification and study of phenomena, where the concept is defined similarly as in the previous paragraph. Indeed, a central tenet of sociohydrology is the observation that coupled human-water systems exhibit complexity features that are comparable to (eco) hydrologic systems, including heterogeneity, cross-scale interactions, emergent behavior (e.g., Sivapalan et al., 2012). Examples of phenomena identified and studied by sociohydrologists include the so-called levee and pendulum swing effects, amongst others (Di Baldassarre et al., 2019). Although early efforts to represent these effects relied on phenomenological models with functional forms very similar to their ecohydrology counterpart, more recent models (a subset of which is reviewed below) reveal a more careful treatment of some of the distinctive features of human systems. While this evolution suggests an increasing (and encouraging) engagement between sociohydrology and the social sciences, cross-disciplinary integration remains a prevailing challenge. Because humans are not driven and constrained by the same sets of first principles as water and ecosystems, the (at times qualitative) phenomenological models developed by social scientists to represent social processes can be very different from the modelling frameworks used by (eco)hydrologists. In that context, an important contribution of sociohydrology has been to establish methodological linkages between (eco)hydrological modelling approaches and frameworks from the social sciences that describe key features of human-water interactions.

A major challenge in that regard has been to capture the complex and heterogeneous nature of (at times qualitative) hydrosocial processes within a quantitative modelling framework (Troy et al., 2015). As Wesselink et al (2017) put it, “this presents epistemological problems: humans differ from other constituents of socio-hydrological models because they can choose how to act on their perception and preferences, and their opportunities for individual and collective agency is affected by socio-political contexts, so no single truth will be found”. Wesselink et al (2017) go on to place sociohydrology within the wider effort in Earth System Sciences, and socioecological systems modeling (SES) in particular, to represent coupled social and physical processes within a single modelling framework (see also Yu et al 2020). Therein, qualitative insights from the social sciences (e.g., institutional analysis and development - IAD) are used to structure quantitative dynamic models. Examples germane to sociohydrology can be found in (Yu et al., 2017; Sung et al., 2018) and (Cifdaloz et al., 2010; Yu et al., 2015;), where IAD has been combined with dynamic systems analysis and the replicator equation to study collective action problems in irrigation and flood protection infrastructure. While these advances are promising in terms of creating a theoretical basis for sociohydrology (Yu et al 2020), much remains to be done to engage with the diverse ontologies (what does the world look like?), epistemologies (what can we know about the world?) and axiologies (how should this knowledge be used?) of the social sciences. These difficult questions have been constructively discussed elsewhere (Rusca and Di Baldassarre, 2019; Wesselink et al., 2017) with helpful pointers on how to address them. Here, we focus on the specific question of modelling human response to hydrologic drivers. Suppose that the above challenges have been adequately resolved in a particular case, so that the specific human decisions that matter, and all their associated social and hydrological drivers have been identified. How, then, might one model the effect of a change in any of the identified drivers on the decision outcome? The challenge in that regard is to produce phenomenological models that are both compatible with (eco)hydrological models and consistent with established theories of human behavior. Some of these models, and their underlying theories, are briefly reviewed in the following section.

3.2. Challenge 2: Modelling human response to hydrological drivers

Two particular theories underpin many recent sociohydrological models: the value-belief-norm (VBN) theory of culture, and the utility theory of rational choice. An important distinction between the two frameworks lies in the way they represent learning -- the process by which individuals change their behavior in response to new information, for instance associated with their perception of hydrological change. Here, we briefly summarize both with respect to their application in sociohydrology for representing human behavioral response to hydrologic information.

The VBN theory is a social-psychological model of environmental decision making used to model feedbacks between the environment and culture (Caldas et al., 2015). In the context of VBN, values are core ideas about right and wrong, three of which have been shown to be particularly relevant for environmental behavior: self interest, altruism towards humans, and altruism towards the environment (Sanderson et al., 2017). Beliefs denote an individual's perception of what is true or false. An individual can update her beliefs in response to new information, but the process is influenced by the individual's values. Beliefs can also be held regardless of empirical evidence. Norms emerge from both values and belief and are rules or heuristics (explicit or implicit) specifying how people should or should not act (Roobavannan et al., 2018). Thus, the extent to which new information alters an individual's beliefs depends on their underlying values (Figure 2A); new information would cause the individual to alter their intrinsic preference.

In contrast to VBN, expected utility theory posits that beliefs are only affected by information (or lack thereof). Beliefs are therefore conceptualized as a probability function that represents an agent's uncertainty on the state of the world. This probability is passed into an expected utility function that expresses the individual's preferences, thereby reflecting their values. The existence of an expected utility function implies that individuals are rational, meaning that they make choices based on a well-ordered preference over outcomes (Von Neumann and Morgenstern, 1953). Action is then driven by the maximizing of the expected utility, accounting for relevant physical, budgetary, cultural (norms) or psychological constraints. Much has been written about the capacity -- and shortcomings -- of utility theory as a model of human decisions (Sen, 1977; Van den Bergh et al., 2000). Relevant to this discussion is the assertion that utility maximization models are phenomenological in nature. They are lumped conceptual models of Homo Sapiens, in the same way that bucket models in hydrology are lumped conceptual models of real catchments (Muller and Levy, 2019). In the same way that bucket models are gross simplifications of real hillslope processes, utility maximization models predict the outcome of decisions without attempting to resolve the sequence of internal psychological, cultural, and social processes behind them (Muller and Levy, 2019). In utility theory new information modifies behavior by affecting the individual's knowledge of the state of the world -- their beliefs. However, their preferences expressed in their utility function, which determines how they would behave if they had full information, remains unaltered and solely determined by their values (Figure 2B). Of note is that expected utility theory presupposes that agents are able to characterize uncertainty and evaluate the probability associated with each state of the word that affects their utility. As a result, it is poorly equipped to handle *ambiguity*: situations where the probability associated with each state of the world is itself uncertain (see, e.g., Harman et al, 2014; Brown et al, 2020).

The implications of this fundamental difference are subtle, but important for normative questions. For example, consider the case of an educational campaign conducted as a part of an epidemiological intervention to prevent waterborne disease (see Section 4). As an information campaign affects beliefs, the risk-benefit analysis of the utility-maximizing individual changes, and he may alter his choice (e.g., to use a new water treatment or hygiene practice). However, since his preference and values are unaffected, the change in his expected utility offers a natural yardstick to measure the welfare-impact of the campaign. In contrast, a VBN agent may change her choice because she experienced a shift in her values, and it is unclear whether the change in her welfare should be computed based on her original or updated value system. The only way to evaluate the intervention in terms of welfare improvement is then to impose an external objective criterion, which presupposes that whoever imposes the criterion knows better than the agent what is best for them, hence the normative question.

Despite their axiomatic differences, the VBN and utility theories are not necessarily incompatible. Norms can often be expressed as a utility function or as choice constraints, and specific behavioral norms that deviate from the rational choice assumption and are of particular relevance to human water interaction (e.g., Prospect Theory, see Section 3.3.2) arguably emerge from perception biases, rather than deeply held values. Notably, a utility function can express values other than self-interest (utility can be derived from somebody else's well-being), meaning that an individual can be both rational and altruistic (e.g., Blanco et al., 2011). As a practical matter, however, economists often stress self-interest as the primary motive in social decision making (Mullainathan & Thaler, 2000) and non-utilitarian frameworks such as the VBN are widely used to model altruistic behavior.

VBN has been extensively used to model the effect of policy intervention on environmental behavior, including in the context of sociohydrology (Sanderson et al., 2017). Its use to represent societal responses to hydrological change, however, is still nascent and typically relies on phenomenological models and calibration techniques borrowed from hydrology and using hydrological data (Roobavanian et al., 2018). In contrast, utility theory has a richer formalism in its representation of human environment interaction that emerged from a long standing focus in economics on behavioral responses to exogenous shocks, including environmental change (see Muller and Levy 2019). In addition, its careful treatment of information and its effect on human decisions mirrors hydrologists' long standing emphasis on hydrologic uncertainty. This potential has been leveraged by an increasing number of studies that combine methods from hydrology and economics to model coupled human-water interactions (Muller and Levy 2019). Here we review a subset of these approaches, which we believe are particularly helpful for hydrologists to consider when modeling human response to hydrological signals (see Table 2).

3.3. Examples of utility-based models of human response in sociohydrology

3.3.1. Evolutionary Games

Evolutionary game theory has its root in the biological sciences as an approach to explain ritualized behavior among animals that appear to contradict the paradigm of evolution. For example, settling disputes by posturing displays, rather than killing their rival, might appear incompatible with an individual's drive to perpetuate their gene pool. Meynard-Smith showed that these characteristics can emerge as an evolutionary stable equilibrium, meaning that a population possessing the relevant trait will dominate after a sufficiently long time (see Hofbauer and Sigmund, 1998). The replicator equation is a central component of these so-called evolutionary game models, where it is used to represent natural selection. Therein, the growth rate of the proportion of organisms using a certain strategy is equal to the difference between the average reproductive success of these organisms and that of the population as a whole (see, e.g., Cressman and Tao, 2014). In effect, replicator dynamics represent the propensity of individuals to copy their most successful peers, a behavioral trait that is known to also emerge in humans (e.g. Schotter and Sopher, 2003). Consequently, replicator dynamics have been used in conjunction with dynamic systems to examine collective action problems around the management of common pool resources, including shared infrastructure (Muneepeerakul and Anderies, 2020).

In sociohydrology, replicator dynamics have been used to represent incentive to cooperate and participate in the maintenance of shared infrastructure, such as irrigation canals or flood protections. The replicator equation captures incentives to free-ride that exist in community infrastructure settings, and how those incentives might be affected by different policies. Yu et al., (2017) used this approach to show that collective action might play an important role in the levee effect, a widely studied socio hydrologic phenomenon describing the relationship between hydrologic variability, infrastructure design and flood vulnerability (see, e.g., Box 1 in Wesselink et al., 2017). Replicator dynamics are compatible with coupled differential equations, making them an attractive tool for (eco)hydrologists to model human behavior. They capture boundedly rational decisions, where agents optimize their utility under limited information (i.e. observing their peers) and are tractable enough to be combined with model structures representing complex institutional frameworks (Muneepeerakul and Anderies, 2020). A helpful introduction to evolutionary game theory and the replicator dynamics is provided in Hofbauer and Sigmund (1998). However, replicator dynamics are rooted in the ecological modeling of (non-human) species and fail to portray important human traits, such as foresight and the ability to act strategically under risk and uncertainty. A more complex paradigm of human response is necessary in situations where these processes are salient.

3.3.2. Microeconomic Theory

By keeping track of the distinct effects of uncertainty (beliefs) and preferences (values) on human decisions, utility theory can represent incentives that might appear paradoxical because driven by noise. If this noise is driven by hydrologic uncertainty, these incentives and the microeconomic models that describe them, are of particular relevance to sociohydrologists. Consider for example the hypothesized relationship between climate change and violent conflicts (Mach et al., 2019). Due to their high costs, disputes that degenerate into violent conflicts are extremely unlikely (Fearon, 1995). Yet conflicts might emerge when the expected future returns from victory exceed the opportunity cost of fighting (Chassang and Miquel, 2009). In an agrarian context, this situation might arise during an abnormally dry year: opportunity costs of fighting instead of ploughing are low because crops do not grow at present, but potential future returns of conquering land are large because crops will grow in the future

(Burke et al., 2015). This mechanism is consistent with a large body of empirical evidence and suggests that hydrologic variability and associated uncertainties have a direct effect on conflict incentives by affecting both the probability and intensity of a “bad” year and the expected water availability (and thus income) in future years (Hsiang et al., 2013). Roche et al., (2020) coupled the above microeconomic model to a hydrological model of water variability to identify the conditions, under which the propensity of conflicts might increase under future climates with increased rainfall variability. This example illustrates how changing hydrologic uncertainty might affect human behavior. However, it does not incorporate the reverse effect of conflicts on water availability, which recent empirical studies suggest might be substantial (Muller et al., 2016).

In contrast, feedbacks between human decisions and water availability are front and center in an increasing body of research considering pumping cost externalities as an important mechanism for groundwater overdraft (e.g., Gardner et al., 1997; Madani & Dinar, 2012; Negri, 1989; Saleh et al., 2011). Therein, individual pumping decisions cause increased pumping costs to all users by decreasing their groundwater levels. Users do not pay the full systemic costs of their pumping and therefore have the incentive to over-pump. This situation is captured by non-cooperative game theory, where the Nash Equilibrium represents the utility-maximizing decision (here pumping rates that minimize volumetric pumping costs) of both players, knowing that the other player maximizes their own utility. For such models, the interface between the economic and hydrogeological components is greatly simplified by the linear nature of groundwater response -- the so-called superposition principle. Complex hydrogeological processes can be simulated numerically using a Finite Difference Model to estimate an aquifer response matrix describing the average drawdown at each player’s wells caused by a unit abstraction from each player’s well fields (Brozovic et al., 2010). The effect of uncertainties, either about the environment (Muller et al., 2017) or about the other player’s strategy (used in Penny et al., 2020 to represent ‘trust’) can be accounted for by choosing the type of game being played. A helpful introduction to applied game theory is provided in Gibbons (1992). We note that pumping cost externalities and groundwater overdraft are one of many examples of misaligned incentives associated with human-water feedbacks (see, e.g., Di Baldassarre et al. 2015 for another example associated with flood protection).

In line with expected utility theory, the above models assume that agents weigh probabilities associated with each state of the world linearly. This assumption is relaxed in Prospect Theory (Kahneman and Tversky, 1979) , where low probabilities are over-weighed compared to high probabilities. For typical humans there is a large, consistent difference between certainty and extremely high probability but not, e.g., between probabilities of 0.99 and 0.991. In the context of sociohydrology, these types of human biases are particularly relevant for phenomena associated with floods (Michaelis et al. 2020, Botzen et al., 2009). As a tractable generalization of the expected utility model, they can be readily integrated in calibrated sociohydrologic models. A second aspect of prospect theory reflects the fact that outcomes are perceived not so much in absolute terms, but framed as losses or gains relative to some reference point. People typically exhibit ``loss aversion'', weighting losses more heavily than gains of the same magnitude. This too is applicable to sociohydrology if there is a natural reference point that can serve to anchor a calibrated model. In Tian et al. 2019, the reference point is agents’ welfare before a persistent hydrological change. However, especially in situations where anticipation about the future affects what is perceived as a `gain' or a `loss', calibration can be challenging in practice.

3.3.3. Macroeconomic Models

Modeling the coevolution between water and society often implies moving beyond the individual decisions considered in microeconomic theory and towards aggregate macroeconomic processes. Much like sociohydrology, where water variables are both affected by and affecting societal variables, most macroeconomic processes have strong endogenous components. For example, in Ramsay's model of economic growth (Ramsey, 1928), a social planner has to decide how much of an economy's output to reinvest in production capital or consumption. The latter determines social welfare, which the social planner wants to maximize, and the former determines production and therefore how much resources there is to distribute in the first place (hence its endogenous nature). These models are firmly grounded in utility theory but typically do not consider water as a salient endogenous variable the way sociohydrologists do. This suggest a potential to (i) use macroeconomic formalism to model sociohydrologic phenomena in a way that is consistent with utility theory, and to (ii) revisit standard macroeconomic phenomena through the lens of water resources. Here we review three emblematic papers that illustrate this potential.

First, Grames et al., (2016) extend Ramsay's growth model to account for the economic effect of flood risk. Similar to the microeconomic model of conflict described above (Roche et al. 2020), the macroeconomic model is driven by hydrologic variability and captures a fundamental tradeoff between immediate benefits (consumption), discounted growth (production capital) and the discounted expected effects of future floods. Incidentally, societal memory is represented (implicitly) in this type of model in a way similar to the representation (explicitly) in other sociohydrologic models (e.g., Tamburino 2020, Di Baldassarre et al., 2015). Ultimately, the model yields multiple equilibria that are broadly consistent with the levee/adaptation effects (Di Baldassarre et al., 2015), where overinvestment in flood protection infrastructure can increase flood risk.

Second, Pande et al., (2014) use an overlapping-generations model (e.g., Galor 1992) to represent endogenous technological change (i.e. the reciprocal relationship between technological change and economic growth, (Romer, 1990), in association with water availability. The model focuses on the productivity of population subgroups, and the relationship of that productivity to technological development. Water, an exogenous production factor, determines the surplus available for both population growth and the development of technology, which then acts as a multiplier to economic production. The model results suggest that endogenous technology development might allow population to increase (albeit unsustainably) despite decreasing water availability. The modeled population soon collapses due to limited water availability, and environmental awareness is renewed. These findings are consistent with the pendulum swing effect (Kandasamy et al., 2014): a sociohydrologic phenomenon that describes the periodic transitions between extractive and conservative water strategies within catchments.

Third, Dang et al., (2016) build on Ohlin's classical trade model (Ohlin, 1933) to account for water as a limiting production factor. They model a domestic water market, where two sectors (agriculture and industry) compete for a limited amount of water. They incorporate the (domestic) effect of international food trade, which is associated with an increase in water use and a decrease in water use efficiency. The paper goes on to evaluate potential policy measures -- namely taxing water use or subsidising water efficient technology -- in their ability to reduce water use without off- setting the economic gains from trade liberalization. Although arguably devoid of features that are uniquely associated with water ("water" in the model could be a variety of production factors), the trade model interpreted through the lens of water produces generalizable insights into the interactions between people and water resources in the context of international food trade.

4. Illustrative example from Epidemiology

Predicting the spread of infectious water-borne diseases is an urgent challenge that embodies the potential for the approaches reviewed in this paper (spatial ecohydrology and sociohydrological models of human decisions) to be combined to address societally relevant contemporaneous issues. In that spirit, we provide a broad overview of the epidemiological setting for waterborne disease research (Section 4.1), highlight relevant recent research from the water sciences (Section 4.1), and propose low-hanging fruit for convergent research (Section 4.3).

4.1. Epidemiology of water-borne diseases

With the understanding that hydroclimatic variability driven by anthropogenic change can increase human health risks, infectious disease has emerged as a focus for both public health and earth and environmental scientists (Metcalf et al., 2017). Waterborne infectious diseases include a large number of pathogens (bacteria, viruses, protozoa, and parasitic worms) with habitats in or transmitted through natural and engineered water systems, contact with which can result in mild to severe illnesses and death in populations worldwide, and in particular in low-income settings and affecting children (WHO, 2019). The presence and type of disease pathogen can vary dramatically in space and in time. For example, waterborne disease pathogens may differ locally within water bodies or along river networks, or may vary intra-annually with season and inter-annually with climate variability and change (Pandey et al., 2014). Human susceptibility to waterborne disease is determined not only by direct exposure to pathogens in water through drinking, bathing, and food preparation, but is also mediated by a number of other direct or indirect social and economic factors: social interactions and mobility, sanitation infrastructure, water collection and storage practices, and hygiene (Levy et al., 2016; Levy et al., 2018).

Epidemiologists have sought to understand and predict the transmission of infectious diseases (including waterborne diseases) using both theoretical and empirical approaches. A common theoretical representation of disease transmission is the conceptual mathematical "compartment model" framework, wherein pools of susceptible, infected, and recovered individuals determine disease dynamics (Anderson and May, 1992; Diekmann and Heesterbeek, 1989). Driving and mediating factors in disease transmission, such as social behavior (Funk et al., 2010), may be represented in such models when those factors are known. However, discovery and analysis of those factors is also typically sought by an empirical arm of public health research, which evaluates the complex relationships between hypothesized drivers of pathogen exposure (social or environmental), disease control (interventions), and disease outcomes (morbidity and mortality) using statistical methods – typically regression analyses (Rubin 2007; Rothman et al., 2008). Many of these research efforts are concerned with accounting for confounding factors (e.g., socioeconomic status, access to improved sanitation) so as to properly understand relationships (Hernan and Robins, 2006). In turn, empirical assessments can refine mechanistic transmission models and guide implementation of public health policy (e.g., education or vaccination campaigns) (Lessler and Cummings, 2016).

A strength of rigorous empirical epidemiological research is the designation – often through large survey data collection efforts – of the myriad social and economic factors that mediate disease and its control (see, for example, the global Demographic and Health Surveys Program or local campaign in Eisenberg et al., 2006). A weakness of these empirical approaches, particular for environmental health investigations, is limited or simplistic accounting of the role of complex physical processes (following from the case study of Eisenberg et al., 2006, see e.g., Carlton et al., 2014 and Levy et al., 2019), including but not limited to the spatial and network processes (e.g., transport, mixing, dilution) that govern the spread of water-born pathogens in hydrologic systems. Historically, spatial methods in empirical epidemiology have included either descriptive approaches (summaries of spatial interpolations and aggregations, or presentation of spatial proximity and clustering analyses) or regression analysis techniques that account for spatial relationships within standard statistical approaches (e.g., geographically weighted regression and Bayesian modeling) (Auchincloss et al., 2012). In the case of waterborne disease, these approaches usually do not capture the fundamental connectivity (e.g. upstream-downstream relationships) of water systems, and the way that societies interact or co-evolve with hydrologic systems, which has the capacity to confound or bias empirical assessments.

On the other hand, several tools from theoretical epidemiological modeling are used to account for complex spatial and network processes: network graph theory models are used to model disease transmission through social or geographic network structures (see Methods described in Section 2.2); metapopulation models combine compartment and network models to represent geographic proximity and nested structures of population subgroups within which disease is transmitted; and agent-based models (ABMs) are used to represent emergent properties of both social and geographic systems responsible for disease transmission (see Stattner and Vidot, 2011). A noted gap in the function of these theoretical modeling approaches is data on population behavior that are used to outfit model functions and parameters. Furthermore, only a small subset of theoretical epidemiologic research incorporates even limited hydrologic processes (see Tien and Earn, 2010 and cholera-specific review in Fitzgibbon et al., 2020), and to our knowledge, none considers human behavioral or adaptive responses to hydrologic change.

4.2. Ecohydrology and epidemiological modeling

Considering the hydrologic and sociohydrologic systems in which waterborne diseases propagate, the gaps in empirical and theoretical approaches discussed above can be seen as posing two main problems: (i) lack of a sufficiently complex representation of physical and biophysical water systems, including their spatial connectivity; and (ii) lack of understanding and documentation of human behavioral responses to water system dynamics and change. While recent advances in both ecohydrology and sociohydrology have the capacity to lend data and models to epidemiologic research (and vice versa), there has been especially notable progress within a rapidly expanding body of literature that applies theoretical hydrologic and social network modeling tools to the study of waterborne disease (Rinaldo et al., 2020). A precise focus of this work has been spatially-explicit modeling of both human mobility and river networks as ecological corridors for waterborne disease pathogens, specifically those responsible for epidemic outbreaks of cholera (Mari et al., 2012; Mari et al., 2019) and the geographic spread of endemic schistosomiasis (Perez-Saez et al., 2015; Mari et al., 2017).

This research targets disease transmission within waterways and river networks that may be characterized as dendritic ecological corridors, and wherein the physical (vs. human or social) component of pathogen transport is governed by fluvial networks (see Ch.4 in Rinaldo et al., 2020 for a complete overview). The core model structure is a spatially explicit nonlinear differential equation model (a compartment-like model) that accounts for (i.e., includes matrix terms describing) both spatial hydrologic and human mobility networks (Gatto et al., 2012; Mari et al., 2012; Rinaldo et al., 2012). A subset of this research additionally extends the model using a periodic (time-varying) dynamical systems approach in order to capture seasonal environmental forcing that can be particularly relevant to environmentally mediated diseases (Mari et al., 2014). While the research is chiefly theoretical, it has been possible to validate model predictions in certain cases, such as in the case of virulent cholera outbreaks in Haiti (Rinaldo et al., 2012) and South Africa (Mari et al., 2012). Notably, the use of cell phone data (as opposed to a gravity model approach) to describe human mobility improved the capacity of these models to represent observed disease dynamics for both cholera (Finger et al., 2016) and schistosomiasis (Mari et al., 2017) in Senegal. While theoretical conditions under which an epidemic can occur or stabilize (i.e. become endemic) have been explored (Mari et al., 2018), case study applications typically focus on the initial invasion or shorter-term spread of disease, and these modeling tools are less well suited to understanding longer-term epidemiological patterns (Rinaldo et al., 2020).

4.3. Promising avenues for research

A tenet of spatial ecohydrologic modeling of this sort is that hydrologic and social networks necessarily constrain patterns in pathogen ecology (Rinaldo et al., 2020). In the case of many diseases, however, these constraints are poorly understood. Pathogen life cycle features vary dramatically across pathogens, and those features often interact with different spatially isolated (incident rainfall) or networked (river flow) components of water systems (see e.g., Kraay et al., 2020). Additionally, human interactions with those water systems, as well as social networks, evolve and change. Thus, an open question is: to what extent do physical (hydrological) and/or social patterns and networks constraint waterborne disease under different conditions, and which is the limiting constraint? This question is of practical importance because whether environmental or social mediators of disease are more relevant to transmission informs appropriate targeting (in time and space) of control measures, such as disease surveillance, education, and vaccine campaigns (Eisenberg et al., 2013; Rinaldo et al., 2020). This is particularly true for endemic water-borne pathogens, for which hydrological systems act as long term natural reservoirs. Pathogens, and the suitability of a given environment to pathogen growth, can coevolve with hydrological systems in a manner that is not unlike any other species endemic to a given environment. However, unlike most species, many pathogens either rely on humans to propagate, or only represent a feature of human interest (i.e., induce human modification of a water system) when they are able to propagate. Therefore, pathogens do not only coevolve with hydrological systems, but also with human systems. Understanding this relationship is critical to evaluate exposure and hence public health risk. Thus, exploring tradeoffs between hydrologic and social mediators of pathogen transmission in determining disease outcomes would be an interesting focus for sociohydrology. Low hanging fruits in this regard include the incorporation of non-stationary hydroclimatic drivers and dynamic human response within this family of existing epi-ecohydrologic models and case studies.

For example, river ephemerality or intermittency has been shown to be relevant to waterborne disease (Perez-Saez et al., 2017) and potentially to its control (Rebaudet et al., 2013); intermittent stream ecology is highly sensitive to hydroclimate variability and change (Chiu et al., 2017). Similarly, populations reliant on intermittent river systems can display dynamic interactions with those systems, and intermittent systems are often highly human-impacted (Leigh et al., 2016; Gordon et al., 2008). Thus, prevalence of waterborne diseases sensitive to the social or physical ramifications of river intermittency might be expected to change dramatically in the long-term, under the combined influence of climate change and human catchment alterations. More generally, efforts to understand long-term waterborne disease dynamics will require sociohydrologists to address both physical/hydrological non-stationarity on one hand, and the adaptive response by individuals and institutions to system perturbations within these already complex systems. This is no simple task, but such convergence can build upon already well-developed modeling tools and data from ecohydrology and social science approaches, and therefore presents an opportunity for sociohydrologic research.

While existing epi-ecohydrological modeling tools have the capacity to be expanded to a variety of other hydroclimate- and hydrology-sensitive waterborne diseases such as Giardia, Cryptosporidiosis, Shigella, and Escherichia Coli infections, to name a few, challenges exist. Many diseases, and particularly less virulent endemic disease, are poorly monitored and measured (Jones et al., 2008); their prevalence in the poorest regions of the world means that risk is confounded with other health vulnerabilities (WHO, 2019); and disease prevalence can be sensitive to often poorly documented social, cultural, or economic behavior (Pattanayak and Pfaff, 2009; Daniel et al., 2020). Many endemic waterborne diseases can therefore prove more difficult to track and attribute, as well as control through intervention, than severely acute and at times more readily traceable and ultimately controllable epidemic outbreaks of severe acute diseases like cholera. A Water, Sanitation, and Hygiene (WASH) sub-field of epidemiology typically operates in the domain of understanding and intervening on social and behavioral dimensions to prevent disease (Bedford et al., 2019). However, WASH research does not typically focus on understanding human or behavioral interactions with physical hydrologic or climate processes, beyond understanding the disease outcome effectiveness of specific intervention tools such as water storage and hand washing practices (Dreibelbis et al., 2013; Daniel at al., 2018).

The difficulty of tackling endemic non-outbreak waterborne disease phenomena is evident especially within empirical public health literature (Levy et al., 2016; Levy et al., 2018; Kraay et al., 2020). However, the increasing availability of both data and modeling frameworks should be read as promising. On the modeling side, research that connects ecohydrologic spatial approaches to human-water system behavioral analyses and models promises to help address waterborne disease prevalence, particularly in low-income settings where the design of effective low-cost solutions is a priority. In the way that recent ecohydrologic approaches to cholera have provided an actionable framework for public health policymakers on disease with outbreak characteristics, similar convergence on prevalent endemic diseases with hydrologic and hydroclimatic sensitivity are low-hanging fruit. Regarding data, there exist a number of public health data sources (e.g., DHS Program; World Bank) as well as private data sources held by government agencies and academic public health groups that might provide ample material for novel public health research focused on human-water systems. In particular, many existing and previously published health data could be re-analyzed from an ecohydrologic - sociohydrologic perspective to gain local to global insights, either through the parameterization of existing models or the development of novel empirical and theoretical approaches. Despite their promise, the sensitive nature of public health datasets (ethical and privacy requirements) is an important challenge to consider. Forging connections with health researchers who are experienced in the management of such datasets is necessary and an acknowledged difficulty in tackling this type of research. Nevertheless, sociohydrology is well poised to tackle this challenge, as we believe that the field has proven to be uniquely amenable to the type of cross-disciplinary collaboration (Figure 1) that makes such activities possible.

5. Conclusion

An expanding set of studies have made substantial strides in linking water resources dynamics with established theories of social interactions and in describing the space-time dynamics of human water interactions. These approaches show great promise for addressing urgent societal needs, such as water borne disease prediction. However, there is to date no unified theoretical framework in sociohydrology to describe the space-time dynamics of water and people. This lack of fundamental principles has stifled the consolidation of knowledge gleaned from the increasing body of case studies and individual modeling efforts. As Troy et al. (2015) put it,

"*First and foremost, unlike in the case of traditional hydrological models, there exist no fundamental concepts (e.g., water balance) or process theories (e.g., process descriptions for infiltration, runoff generation, evaporation, etc.) let alone governing equations, to guide the development of sociohydrological models".*

In other words, sociohydrological models tend to be developed inductively: phenomenological models (often rooted in the hydrological sciences) tend to be assembled in conceptual frameworks to qualitatively match an observed phenomenon. To create knowledge that is both generalizable and actionable, the field needs to transition towards a theory-driven deductive approach that is more in line with the scientific method of hypothesis testing (see Muller and Levy 2019). Given the historical and methodological parallels between the two fields, the theoretical framework associated with ecohydrology, and coupled social-ecological systems more broadly (see Yu 2020), can serve as a promising starting point. Conversely, an explicit link to ecohydrology would make it easier for sociohydrologists to leverage and adapt rapid recent theoretical developments in our understanding of water-ecosystem interactions -- particularly in the spatial domain -- as they pertain to human water interactions.

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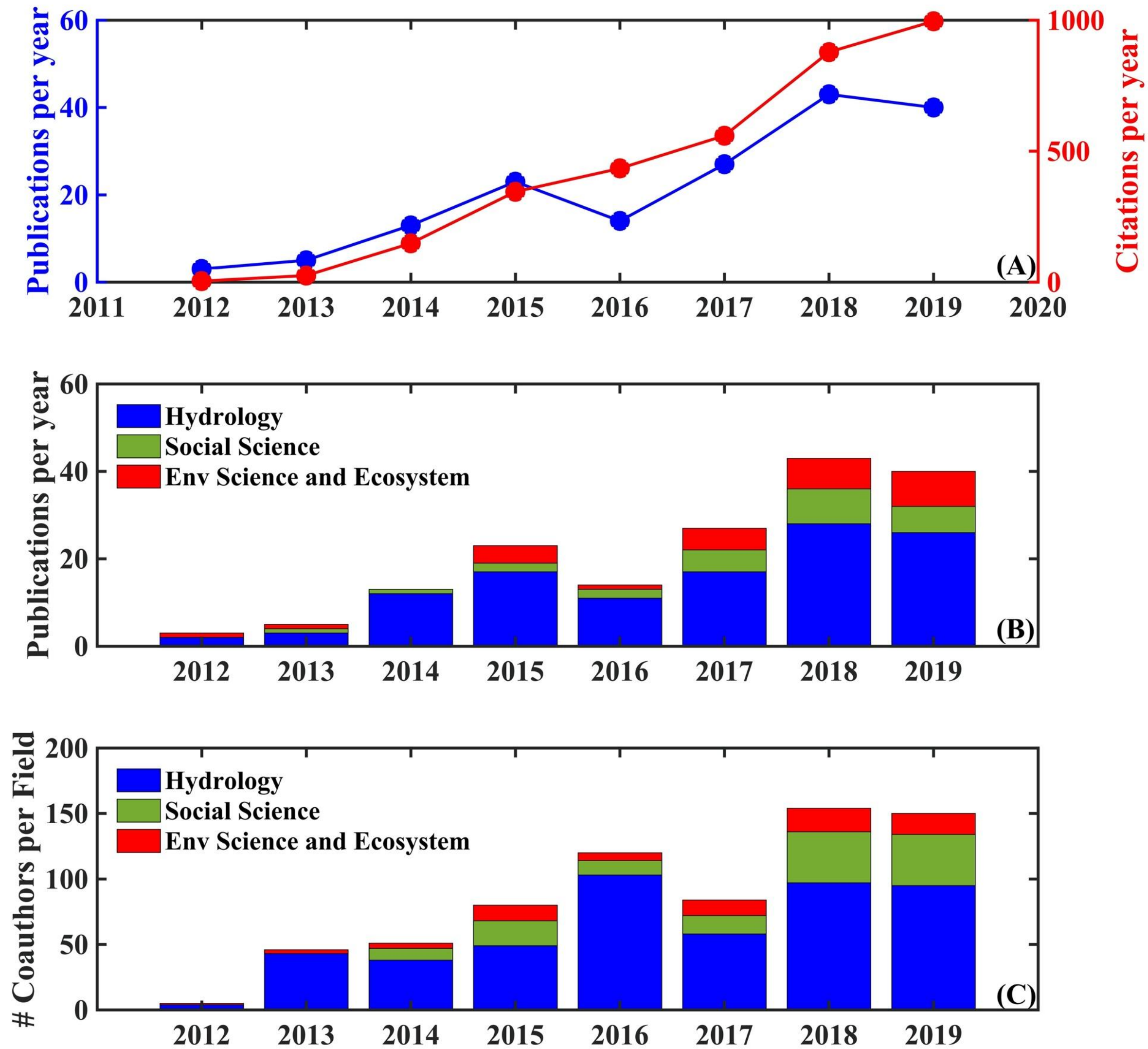

Figure 1: (A) Comparison between the time series of sociohydrological related publications per year and the corresponding number of citations. (B) Temporal trend of the corresponding leading author (B) and co-authors (C) by academic research field. The dataset of sociohydrologic publications was collected and curated by Madani and Shaffie-Jood (2020) based on a serie Web of Science keyword search (see Madani and Shaffie-Jood, 2020) for specific details. The dataset includes 180 papers, cited 3756 times overall based on Web Of Science citation report, with 593 contributing authors. Academic fields were manually assigned to authors based on their previous work and institutional affiliation.

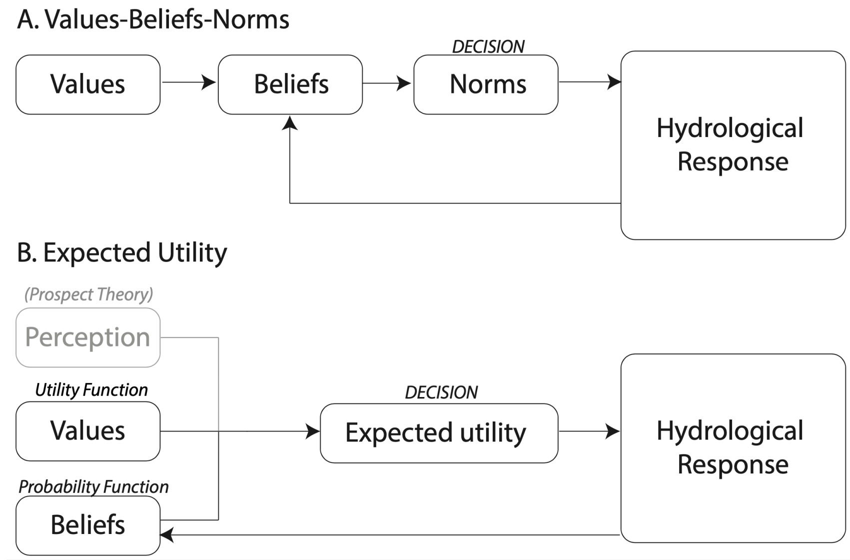

Figure 2: Representation of sociohydrologic feedback in the Values-Beliefs-Norms (A) and Expected Utility (B) frameworks. Values influence the extent to which hydrological change causes agents to update their belief in the VBN framework, but not in the expected utility framework.

Table 1. Similarities between human migration and species dispersal

	Attractiveness	Distance	Limitation
Human Migration	Economic welfare (e.g., higher wages, health care, education) Political stability (e.g., absence of conflicts and/or persecution) Better climatic conditions (e.g., sea level rise, hurricane, etc.) Viability of origin node	Geographical distance Cultural distance (e.g., religion) Different languages	Regulations governing immigration into that country Cost of moving
Species Dispersal	Larger resources availability (e.g., food, mates) Secure refugia from predators	Geographical distance among suitable habitats	Physical barriers to migration (e.g., road network)

Stable from environmental shocks (e.g., floods, fires, etc.) Viability of origin node		Presence of predators along the dispersal path

Table 2. Reviewed utility-based models of human response

	Tool	Problem addressed	Application Example
Evolutionary games	Replicator dynamics	Collective Action (Myopic)	Shared infrastructure maintenance (Yu et al., 2017)
Microeconomics	Expected utility theory	Opportunity costs (Rational Agent)	Water variability and conflicts (Roche et al., 2020)
	Non-cooperative game theory	Collective Action (Foresight)	Shared groundwater management (Muller et al. 2017)
	Prospect Theory	Opportunity cost (Behavioral Biases)	Water use & decadal climate variability (Tian et al. 2019)
Macroeconomics	Ramsey Growth Model	Opportunity cost (Risk Mitigation)	Societal memory and the levee effect (Grames et al., 2016)
	Overlapping generations Model	Endogenous growth	Pendulum swing effect, societal collapse (Pande et al., 2014)
	Heckscher-Ohlin trade Model	Input factor allocation	Policy evaluation of water taxes & subsidies (Dang et al., 2016)

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