Complementary vantage points: integrating hydrology and economics for sociohydrologic knowledge generation

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Abstract

Because human and environmental systems in the Anthropocene are increasingly coupled, hydrologists and economists often find themselves studying the same systems from different vantage points. Here we argue that synthesis across economics and hydrology can help address two pressing sociohydrologic challenges: actionable prediction and the generation of transferable knowledge from place-based studies. Specifically, we review (1) empirical methods and (2) theoretical approaches from economics, and connect the two through a proposed iterative framework. First, we find that empirical methods for statistical analysis of natural and quasi experiments in economics can be leveraged to distinguish causal relations from mere correlations in complex and data-scarce systems, which can help address the challenge of sociohydrologic prediction. Second, we find that economic theories based on rational choice can be used to decipher known paradoxes in water resources, which can help address the challenge of sociohydrologic knowledge generation. In both empirical and theoretical domains, specialized knowledge in hydrology remains critical to properly applying techniques from economics to coupled human-water systems. We propose that linkages between the two fields highlight a large potential for interaction.

1 Introduction

Rapidly growing human populations perturb natural ecosystems and landforms. In doing so, humans simultaneously influence and are influenced by the availability of water resources to support life and economic activity. This human-water feedback emerges as a fundamental characteristic of hydrologic systems in the Anthropocene [Sivapalan et al., 2012], and compounds two key contemporary issues in water resources management. First, the global frontier for addressing water management problems is shifting towards developing country regions, where most of the world’s population currently resides, where the most critical water crises are anticipated to occur, and where the preponderance of development of land and water resources will take place in coming decades [Srivastavan et al., 2012; Padowski et al., 2015]. Problematically, these regions typically offer only sparse reliable observational information [Blöschl, 2013], which makes evaluating and addressing critical challenges difficult. Second, the combination of anthropogenic drivers such as rapid demographic change, climate change and variability, and land cover conversion now forces hydrologists to confront the implications of non-stationarity on hydrologic prediction [Milly et al., 2008; Thompson et al., 2013]. Non-stationarity is expected to par-
particularly confound prediction in developing regions, where climate change is projected to have outsize consequences [e.g., Huang et al., 2016].

These issues have long been recognized by the hydrology community, and a substantial body of recent research has been devoted to developing tools for hydrologic prediction in data-scarce (e.g., the Prediction in Ungauged Basins, or PUB initiative [Blöschl, 2013; Hrachowitz et al., 2013]) and non-stationary conditions (e.g., predictions under change, or Panta Rhei initiative [Montanari et al., 2013; Thompson et al., 2013]). Water resources science also has a long history of incorporating anthropogenic drivers for water resources systems analysis [Brown et al., 2015], frequently relying on tools from the field of economics. The Harvard Water Program pioneered the incorporation of social and economic variables into analyses of water system engineering design as early as the 1960s, and considered the socioeconomic and environmental tradeoffs of water infrastructure projects [Maass et al., 1962; Reuss, 2003]. Called for a hydrology sub-field incorporating social processes for water system planning purposes. Development of hydro-economic models proceeded from the 1970s [e.g., Young and Bredehoeft, 1972; Cai et al., 2003a,b,c], and the field is especially well known for its contribution to improving operational forecasts for water management [Harou et al., 2009]. Integrated water resources management [Kadi, 2014] emerged in the 1990s with a focus on maximizing benefits of water management across stakeholders, and decision-oriented watershed management models that incorporate social and economic factors continue to be developed [see Vogel et al., 2015]. Calls for the integration of social and hydrological process feedbacks into global-scale hydrological models appear as early as the 1980s, and some global hydrology and water resource models [Bierkens, 2015] and earth system models [Calvin and Bond-Lamberty, 2018] provide capacity to model the effects of economically-motivated human drivers such as land use change. These efforts produced a rich array of tools to optimize water management decisions and assess their impact, typically through scenario-based analysis [e.g., Cai et al., 2002].

The nascent field of sociohydrology complements these initiatives by taking a distinctively positivist approach to coupled water-human systems (i.e., an approach focused on system understanding) that contrasts with the normative nature of previous research efforts (i.e. those focused on identifying solutions to specified problems) [Sivapalan and Blöschl, 2015; Pande and Sivapalan, 2017]. Deciphering fundamental principles that regulate the co-evolution of humans and water, a process which we refer to as sociohydrologic...
knowledge generation, is a central tenet of sociohydrology \cite{Sivapalan et al., 2012; Sivapalan and Blöschl, 2015}. Thus, the boundaries and drivers of sociohydrologic systems are typically not prescribed using predefined scenarios, but rather endogenously determined by intrinsic dynamics of the system, for instance related to interactions between short and long time-scale processes \citep[see e.g.,][]{Pande and Sivapalan, 2017, for further discussion on the distinctive features of sociohydrology}. This focus on human-water interactions across scales implies that reckoning \textit{simultaneously} with non-stationarity, data-scarcity, and anthropogenic feedbacks is a core challenge of sociohydrologic research.

Here, we argue that economics offers useful methodologies for sociohydrologists to consider when addressing this three-fold challenge. Like hydrology, economics evolved from a largely qualitative and empirical discipline into today’s heavily quantitative mathematical science, which makes the two fields methodologically compatible. Economics has also branched out into several multi-disciplinary fields, among which environmental economics addresses the management of natural resources, including water \citep[see reviews in][]{Booker et al., 2012; Hanemann, 2006; Chong and Sunding, 2006; Schoengold and Zilberman, 2007}. Thus, today’s environmental economists and hydrologists often find themselves studying similar coupled human-water systems from different vantage points and, unsurprisingly, they face similar challenges. The economic and hydrologic perspectives are complementary, and this review suggests, individually incomplete. This complementarity motivates an integrated two-way interdisciplinary approach combining methods from economics and hydrology within sociohydrology, the scope of which we only begin to explore in this review.

To be sure, combining hydrology and economics is hardly a new proposition. For instance, the economic concept of utility (usefulness or benefit to an actor or agent) has long been used to model water use \citep[e.g.,][]{Young and Bredehoeft, 1972}, optimize decisions \citep[e.g.,][]{Maass et al., 1962}, and analyze uncertainty \citep[e.g.,][]{Wood, 1976}, institutions \citep[e.g.,][]{Saleth and Dinar, 2004} and welfare \citep[e.g.,][]{Leggett and Bockstael, 2000} in coupled human-water systems. Hydro-economic models integrate the economic notions of scarcity and value by representing water demand as an explicit function of water availability, rather than a fixed volumetric requirement \citep{Harou et al., 2009}. These insights allowed researchers to assess, for instance, the potential for markets to mitigate the effect of climate variability \citep{Characklis et al., 1999}, to evaluate the effectiveness of water use efficiency improvements \citep{Rosegrant et al., 2000}, and to estimate the effect of hydrologic
prediction uncertainties on water infrastructure decisions [Anghileri et al., 2016; Müller and Thompson (2019), In Press]. However, we argue that stronger integration between economics and hydrology will help both fields address two key methodological problems that emerge when studying human-water interactions in data-scarce and non-stationary environments:

1. Empirical causal inference: Causal relationships are challenging to distinguish from mere statistical correlations in empirical (data-driven) research due to feedbacks and data limitations.

2. Theoretical explanatory power: Inadequate theoretical treatment of dynamic feedbacks between humans and water gives rise to paradoxes that cannot be resolved by hydrology or economics alone.

This review was written to provide sociohydrologists with new tools for causal empirical inference (Section 2) and argue for a stronger integration of theoretical economic principles in the development of sociohydrologic theory (Section 3). Both sections review these core challenges as they emerge in sociohydrology (Sections 2.1 and 3.1), and as they appear in economic approaches (Section 2.2 and 3.2). We then review recent literature in both fields, focusing on research that applies a selection of economic tools to facilitate causal inference (Section 2.3), and on water-resources paradoxes that are propitious to joint theory development efforts (Section 3.3). Section 4 discusses how progress on both fronts (empirical and theoretical) can be leveraged to generate transferable knowledge from place-based studies, which is a fundamental unsolved challenge in sociohydrologic research [e.g., Troy et al., 2015; Brown et al., 2015; Thompson et al., 2013]. Therein, we introduce an iterative framework that formalizes the idea that sociohydrologic research will advance through empirical and theoretical interplay [Troy et al., 2015] within the hypothesis generation and testing cycle standard to scientific inquiry [Pande and Sivapalan, 2017].

When pointing to economics as a promising toolbox for sociohydrology, we stress three important points. First, not all data and problems are suited to economic analytic approaches. While the compatibility between economics and hydrology creates clear avenues for joint research, methods from other disciplines, including the qualitative social sciences, remain critical to understanding coupled human water systems [Dobbie and Brown, 2014; Leong, 2018; van Rijswick et al., 2014; Wesselink et al., 2017]. Second, the continued relevance of approaches from ‘traditional’ hydrologic sciences should not be discounted. In
reviewing recent literature at the economics-water interface, we found that a solid understanding of natural processes is key to actionable implementation of economic tools. In particular, we found that an explicit representation of hydrologic processes can offer new directions to address long standing challenges in economics, both in the empirical (e.g., Section 2.3.1) and theoretical (e.g., Section 3.3.1) realms. Lastly, we stress that this review provides only a cursory introduction to sociohydrology-relevant economic approaches, intended as an initial road map for the interested reader.

2 Problem 1: Empirical Causal Inference

2.1 Challenge: Correlation does not imply causation

Establishing that one observed phenomenon *causes* another (i.e., causal inference) is essential for testing theoretical hypotheses and making reliable predictions [see Pande and Sivapalan, 2017; Srinivasan et al., 2017, for further discussions of the definition and challenges of sociohydrologic prediction]. Doing causal inference in dynamic system settings is not trivial. Observed correlations may not imply causation due to complexity and feedbacks. To illustrate this point, consider the relation between a country’s openness to international trade and its domestic water consumption, which is an important question in sociohydrology that speaks to the ongoing debate on globalization and the environment (see Section 3.3.3). Statistical analyses of transnational data show significant negative correlation between trade openness and water use when controlling for factors like the size of the economy [Kagohashi et al., 2015]. In other words, countries that trade more tend to use less water. However, this does not necessarily mean that countries use less water because they trade more. For instance, arid countries may engage in trade precisely because they consume less water, so a reverse causal relationship could have well given rise to the observed correlation. Further analysis is needed to determine whether trade has a causal effect on water consumption. The pitfalls of causal inference using observational data are increasingly recognized in the coupled human-natural systems literature [Ferraro et al., 2018], but less so in water resources. Here, we frame the issue of causal inference within the specific context of sociohydrologic systems. We argue that sociohydrologic systems are inherently well suited to approaches developed in econometrics, the field of applied economics focused on statistical methods.
Ordinary least squares (OLS) multivariate regression is an important statistical workhorse of empirical analysis in many fields, including hydrology [Ward et al., 2015, Ch. 1.6], and in empirical economics [for an introduction and overview, see Angrist and Pischke, 2009, Ch.3], wherein it is often used to evaluate causal hypotheses in specific settings known as natural experiments and quasi-experiments (see Section 2.2). Regression analyses provide estimates of average change and associated error in an outcome or dependent variable (left hand side of a regression equation) with respect to levels of change in an independent or explanatory variable of interest (right hand side), holding all other independent variables constant. Note that although OLS is a linear regression framework, nonlinear relationships can be handled by way of data transformations or non-parametric estimation [Davidson and MacKinnon, 2003; DiNardo and Tobias, 2001]. Regression analysis specifications often respond to dynamics expressed in theory, and provide policymakers and planners with predictions that are explicit with respect to statistical rather than process-based uncertainty.

To be interpreted causally, regression analyses should be structured around what are known as natural experimental or quasi-experimental analysis designs (see Section 2.2), and causal interpretation requires that explanatory (right hand side) variables are ‘exogenous’. Exogeniety implies that explanatory variables are statistically independent of the error term of a regression; the error term captures unexplained variation in the outcome variable [Wooldridge, 2015]. Common causes of dependence (the non-independence of explanatory variables), or ‘endogeneity’, are referred to as ‘reverse causality’ and ‘omitted variables’ (Figure 1). Reverse causality arises when the dependant variable (the outcome) might have influenced the independent variable (the driver or cause), as in the trade example discussed above. The second form of endogeneity arises when the researcher is not able to observe a variable that is correlated with both the dependent variable (the outcome) and the independent variable under consideration (the driver or cause). To return to the trade example, both trade openness and water use could be (independently) determined by a country’s political ideology or institutional history. These represent potentially important omitted variables that might explain the observed correlation. Endogeneity is problematic because it introduces bias in regression results [see Angrist and Pischke, 2009;
Wooldridge, 2015]. That is, the amplitude, direction, or statistical significance of a causal relationship may be misrepresented by ordinary least squares estimation.

Endogeneity can emerge in many circumstances, and arguing that any variable in a tightly coupled sociohydrologic system is truly exogenous is challenging. It is important to note, however, that the extent to which the ensuing bias is substantial enough to affect research outcomes varies, and scale considerations are important. For instance, economists commonly use climate as an exogenous variable [see e.g., Schlenker et al., 2005]. Although human influences on the climate are well established, these effects play out at spatial and temporal scales that are very different from investigated social processes, and therefore consideration of climate as exogenous may be acceptable in certain circumstances. Similarly, in their sociohydrologic study of community-managed water systems in New Mexico, Gunda et al. [2018] treat crop prices as exogenous under the assumption that local agricultural production is too small to influence regional market prices. Nevertheless, in many cases, observed variables are endogenous to a system at scales that are relevant to the tested hypothesis, and the ensuing biases have to be dealt with explicitly.

2.2 Approach: Natural Experiments and Quasi-Experiments

In a true experiment, the researcher controls the random a priori assignment of study subjects to compared (control and treatment) groups. True experiments are the gold standard for causal analysis, as randomization accounts for possible alternative explanations for an observed relationship between a driver and an outcome of interest, which can otherwise bias estimation and attribution of effects [see Angrist and Pischke, 2009; Imbens and Rubin, 2015]. A parallel in hydrology can be found in physical experiments that have been critical to understanding fundamental principles [e.g., Darcy’s law Darcy, 1856]. In the social sciences, however, tools for experimentation (e.g., randomized control trials [see Duflo et al., 2007]) and the scope of experiments are often limited by costs and ethical constraints. This often forces social scientists to rely on observational (non-experimental) data to investigate hypothesized causal relations and address the endogeneity concerns that emerge in that process [see Angrist and Pischke, 2009; Rosenbaum, 2010; Sobel, 2000].

To address endogeneity, many applied economist rely on the Rubin Causal Model [Rubin, 2005], a core conceptual model that defines causal effects as those achieved by
Figure 1. (a) Causal diagram of the relationship between trade openness and water use. Common endogeneity problems (dashed arrows) include: (i) omitted variables (e.g., wealth affects both water use and trade openness) and (ii) reverse causality (e.g., water use can increase trade openness by empowering agricultural lobbies). Dang and Konar [2018] address these concerns by using geographic determinants of trade (e.g., distance) as instrumental variables (iii). (b) Difference-in-differences is used to estimate the effect of the 2013 refugee crisis on irrigated land area in Southern Syria using Northern Jordan as a control group [Müller et al., 2018a]; error bars indicate standard deviations across years. (c) Regression discontinuity to estimate the effect of alcohol on young adult mortality [Carpenter and Dobkin, 2009]; lines indicate non-parametric regression predictions.

comparing the outcome of alternative scenarios (counterfactuals) under different conditions [see Angrist and Pischke, 2009; Imbens and Rubin, 2015; Heckman, 2005]. Practically, use of the Rubin Causal Model in empirical studies involves the design of a hypothetical ideal experiment. This allows a data-analysis approach to be developed that best approximates, or mimics, an ideal experiment with observational data [Angrist and Pischke, 2009]. Data are analyzed such that the driver of interest is as good as randomly assigned across observation units (see examples in Section 2.3). This allows the researcher to effectively control
for other potential confounding factors influencing the outcome, and investigate the particular causal relation of interest [Angrist and Pischke, 2009; Imbens and Rubin, 2015].

This approach requires that the observational dataset either (i) emerges from a natural experiment, where an exogenous ‘natural’ event (not controlled by a researcher) appropriately randomizes observation units into comparison groups, or (ii) allows for a quasi-experiment, where specific attributes of observation units allows their ex post assignment to appropriately randomized control and treatment groups. Parallels to both natural and quasi-experiments in hydrology can be found within paired basin studies [Brown et al., 2005], where researchers exploit contrasting attributes of otherwise similar river basins to understand the effects of change (e.g., in land cover) on hydrology. Under natural or quasi-experimental conditions (further discussed in Section 2.3) a statistical model estimating the effect of a driver on an outcome is said to be well identified: estimated parameters (e.g., regression coefficients) can be interpreted causally because they do not also capture the effect of unobserved and/or confounding drivers. Note that the meaning of identification in economics [see Koopmans, 1949] is fundamentally similar to that in hydrology [see Beven and Freer, 2001]: a parameter is identifiable within a model if it is possible to uniquely estimate. Because requirements for identification limit the extent to which empirical analyses are causal, alternative approaches to causal analysis (e.g., from the qualitative social sciences [Wesselink et al., 2017]) can be invoked when observations do not allow for a natural or quasi-experimental approach.

Use of natural and quasi-experimental approaches to identify causal relationships originated in labor economics [LaLonde, 1986; Card, 1990] and subsequently spread into other economic fields, including environmental economics [Chay and Greenstone, 2003, 2005; Fabrizio et al., 2007]. These approaches have been used by water resources economists to characterize water demand [Schoengold et al., 2006; Schoengold and Sunding, 2014; Buck et al., 2016] and to study the welfare and economic impact of water provision [Buck et al., 2014; Schlenker et al., 2007; Buck et al., 2016; Duflo and Pande, 2007]. Use of natural and quasi-experiments to support causal empirical research in sociohydrology is emerging, particularly in data-scarce regions. A handful of recent studies have leveraged hydrologic modeling and remote sensing to conduct causal inferences in regions that are inaccessible due to remoteness [Müller et al., 2018a], ongoing conflict [Müller et al., 2016] or political barriers [Müller et al., 2017b], or where the limited size or representativeness of
standard hydrologic monitoring data otherwise prohibits cross-scale generalization [Levy et al., 2018].

As research design is central to causal identification, the possibility of using natural or quasi-experimental approaches depends critically on the characteristics of the observational data at hand, and on the researcher’s knowledge of the data-generating process (i.e., of hydrology). In fact, a core component of applied economic research is identifying clever natural experiments (events that randomize units of observation in a way that allows testing of a hypothesis) or quasi-experimental approaches (introduction of an instrumental variable into analysis of observed data - see Section 2.3.1), making water scientists particularly well equipped to identify natural experiments and quasi-experimental approaches in sociohydrological systems. Consequently, there is scope for collaboration between economists and hydrologists on the proper use of identification approaches, even when addressing core economic questions. In that spirit, and to facilitate literacy with key econometric techniques, we turn to a summary description of specific tools used in causal inference - within both natural and quasi-experimental settings - that we find to be useful for the analysis of sociohydrologic systems. We refer the reader to Angrist and Pischke [2009] for an extended accessible and comprehensive review of econometrics and its application.

2.3 Applications: select econometric tools for sociohydrology

2.3.1 Instrumental Variables

Use of instrumental variables (IV) [see Angrist and Pischke, 2009, Ch. 4 for implementation details] is a particularly popular approach for addressing endogeneity in economics [see Schoengold et al., 2006, for a water resources example], although it is still infrequently used by water resources scientists. This approach can be used with cross-sectional observations (of multiple subjects at the same time), as well as data characterized by repeat observations of one or more subjects over time (longitudinal or panel data), which may be more difficult to obtain. An IV is a variable that is strongly correlated with the independent variable of interest (the driver), but does not affect the dependent variable (the outcome), other than through its effect on the driver (Figure 1 (iii)).

Dang and Konar [2018] used this approach to address endogeneity in the example discussed in Section 2.1, when estimating the effect of a country’s openness to interna-
tional trade on domestic water withdrawals for agriculture. The *Dang and Konar* [2018] study is an example of a quasi-experimental approach that compares countries across levels of trade openness (i.e., ‘comparison groups’ are levels of trade openness). Building on previous empirical studies in trade economics [e.g., *Frankel and Romer*, 1999], *Dang and Konar* [2018] used geographic distance between the countries as an IV - a variable that affects trade openness (the hypothesized cause), while not directly affecting domestic water withdrawals (the effect). Under these conditions, any correlation that emerges between the IV and the effect arises from the causal relationship under investigation (the effect of trade on water withdrawals). Using this strategy, *Dang and Konar* [2018] found that trade openness has a negative effect on domestic agricultural water use and discussed trade-related incentives for farmers to improve water use efficiency as a possible mechanism.

Again, it is crucial for an IV (i) to be strongly related to the independent or explanatory variable (the driver) under investigation, and (ii) this strong dependence must emerge for all observations the dataset. However, (iii) the IV should not be directly related to the dependant variable (the outcome). Finding a valid instrument satisfying all three conditions can be very challenging. As economists are increasingly making use of natural environmental features (climate, topography) as IVs [e.g., *Miguel et al.*, 2004; *Duflo and Pande*, 2007; *Lipscomb et al.*, 2013], hydrology stands to make key contributions to the identification of new, effective IVs [see e.g. *Rud*, 2012; *Müller et al.*, 2018a] that are successful in addressing endogeneity concerns in causal analyses of water resources. Thus, while endogeneity issues are pervasive in coupled human-water systems, so are water variables that may be used as instruments to address endogeneity. IV is therefore a particularly promising avenue for causal empirical analysis in sociohydrology.

### 2.3.2 Fixed effects

Fixed effects (FE) can be used to address endogeneity when the available data allow spatial and/or temporal variations to be observed (e.g., when using time series, cross-section, or panel datasets). Simply, FE is implemented by adding indicator or dummy variables for observations associated with different groups or time periods in a regression. These indicator variables will control for unobserved variations associated with a given group or time [see *Angrist and Pischke*, 2009; *Wooldridge*, 2015, for implementation details] [and *Wooldridge*, 2010, for an in-depth discussion of this and other available methods]. For example, *Hendricks and Peterson* [2012] used a fixed effects strategy to es-
timate the price elasticity of irrigation water demand (change in irrigation water use with the costs of electricity for groundwater pumping) based on farm field-level panel data. Use of their data in a regression framework for direct causal inference is problematic because farms with greater depths to groundwater (greater pumping costs) may also have physical attributes (soil properties) that are correlated with water demand, which would bias the estimate of the sensitivity of water demand to costs. Therefore, Hendricks and Peterson [2012] use farm and year fixed effects to control for this correlation and isolate the role of groundwater costs. In a study on national trends in drinking water quality violations in the US, Allaire et al. [2018] control for state (regulations are enforced at the state level) and year (regulations change over time) fixed effects in a panel regression. This allowed utility-level vulnerability factors to be identified, and their causal effect on water quality violations to be estimated. Khan et al. [2017] use econometric techniques to analyze global data on water features and runoff, climate, infrastructure, and institutions in order to estimate the effects of water-related hazards on economic growth. The authors explore standard econometric techniques for handling endogeneity, including (but not limited to) country and year fixed effects to control for omitted variables that vary across locations and time.

While space and time dummy variables are ubiquitous in econometric applications, and are used in most of the applied economic studies referenced in this review, the above studies demonstrate how their implementation plays a key support role in identifying causal human-water relationships. Although panel data, which are particularly suited to FE estimation approaches, can be challenging to collect in situ for sociohydrologic systems, new sources of space-time (e.g., remote sensing [see Levy et al., 2018, for example]) or individual-time (e.g., social sensing [Wang et al., 2015]) observations are particularly promising. Finally, we note that FE is one of several (related) methods for causal inference using panel data, which are further discussed in specialized literature [e.g., Wooldridge, 2015, Ch. 14]

2.3.3 Difference-in-differences

Difference-in-differences (DID) is a regression modeling approach for observational panel data. Intuitively, DID establishes what an outcome “would have been” in the absence of some treatment or exposure (driver) under consideration. The standard DID approach allows statistical comparison between data from two groups and over two peri-
ods of time, within which a treatment or exposure occurs for one group (the "treatment" group) in one time period, but not for the other group (the "control" group). DID provides a straightforward estimation of the average change in an outcome variable for a treated group relative to the control group over a shared period of time [Ashenfelter and Card, 1985; Card and Krueger, 1994]. Formally, the DID estimate of the effect of a treatment is the difference between mean observed values in the treated group between the two time periods, minus the difference between mean observed values in the control group between the same two time periods (Figure 1 b). This design controls for confounding factors that either occur simultaneously with the treatment (i.e., between periods) and affect both groups, or only affect the treatment group but in both periods. Causal identification hinges on the critical assumption that outcomes in both groups would follow identical trajectories (but not necessarily have the same value) absent the treatment [see Angrist and Pischke, 2009, Ch. 5 for implementation details].

Commonly, this method is used for policy evaluation, and economists have used DID to evaluate human and environmental responses to water policy and management programs. For example, Nataraj and Hanemann [2011] use a DID approach to estimate urban water demand elasticity (change in household water use with price) by framing a change in a water utility’s price structure (the division of the highest block of an increasing block pricing scheme into two blocks) as a natural experiment; they compared water use between two groups of otherwise similar water users, before and after the price structure change (see also Section 2.3.4). In an economic study of trends, causes, and social welfare consequences of water pollution in the U.S., Keiser and Shapiro [2017] aggregate water quality, climate, and social data, and estimate the effect of Clean Water Act (CWA) grants to water treatment plants on water pollution in the U.S. Their DID approach is structured around the fact that areas directly upstream of a water treatment plant may be compared to areas downstream of the plant, before and after the CWA. This study provides a useful example of the use of natural hydrologic features to engineer a natural experimental analysis design.

While use of DID is limited in the water sciences to date, this approach is gaining traction for evaluating human or hydrological responses to anthropogenic change. Motivated by the fact that research examining the effects of deforestation on streamflow was incomplete with respect to the production of regional, cross-scale empirical understanding relevant to policy, Levy et al. [2018] use a DID approach to compare catchments with
low and high levels of deforestation, before and after the onset of agricultural development, quantifying average regional increases in flow following deforestation using satellite and in-situ data. This DID approach controlled for confounding factors (i.e. climate), and enabled comparison across many basins that were not otherwise directly comparable using more traditional time series hydrologic approaches (e.g. paired basin analyses) due to regional data limitations. Müller et al. [2016] show how conflict-driven abandonment of irrigated agriculture in war-torn Syria resulted in increased transboundary streamflow to Jordan. This study used satellite imagery to investigate causal relationships between changes in land use and water resources using a DID approach, wherein Syrian regions were compared to non-Syrian regions without conflict or emigration, before and after the year of heaviest migration in Syria. The approach was critical to disentangling the confounding effects of migration (only in Syria) and climate (in Syria and Jordan) on the streamflow increase. Both studies give insight into how natural experimental empirical methods that make use of remote sensing data are especially useful for understanding land use and hydrologic dynamics in unstable, inaccessible, or data-poor settings. While both studies focus on biophysical processes driven by human action, they provide examples of how diverse environmental and hydrologic datasets, combined with social data, might be used to elucidate sociohydrologic dynamics.

2.3.4 Regression Discontinuity

Regression discontinuity (RD) designs are customarily used to estimate the outcome of a treatment by assigning a cutoff or threshold at the point where the treatment was administered. The cutoff may be defined as a point in time [e.g., Nataraj and Hanemann, 2011, see below], a spatial threshold [e.g., Sekhri, 2014, see below], or another (e.g., administrative) cutoff [e.g., Nataraj and Hanemann, 2011, see below]. The effect of a treatment is evaluated by comparing outcomes just around the threshold or ‘discontinuity’ [see Thistlethwaite and Campbell, 1960; Imbens and Lemieux, 2008; Angrist and Pischke, 2009, for implementation details]. Causal inference hinges on the assumption that the outcome would have been identical for observations taken just around (e.g., above and below) the threshold, save for the intervening treatment.

For example, in a classical social science implementation of RD, Carpenter and Dobkin [2009] use the discontinuity at the minimum legal drinking age (21 in the US) to evaluate the effect of alcohol consumption on young adult mortality. RD addresses omi-
ted variable biases that may arise from unobserved factors affecting both youth drinking
and early mortality. Assuming that these variables similarly affect individuals just below
and above legal minimum drinking age, the rise in mortality detected at age 21 was in-
terpreted as the causal effect of alcohol consumption (Figure 1 c). Similarly, in the study
of urban water demand elasticity by Nataraj and Hanemann [2011], the identification of
a discontinuity was fundamental to the DID design (see Section 2.3.3). Water users were
assigned to comparison groups according to their historical water use being just above
or below the new threshold in a revised block price structure. Thus, water users were
selected into treatment and control groups according to a near-random process, creating
the conditions under which this study was arguably causal. A creative application of RD
to water resources is described in Sekhri [2014], a study in development economics that
estimated the effect of groundwater access on poverty in India. Groundwater access and
poverty are endogenous because wealth improves one’s ability to exploit groundwater (e.g.,
by enabling investment in better pumps). Sekhri [2014] exploit a threshold in groundwa-
ter depth that prescribes the use of pumping technology: households with water tables just
above a depth threshold can use cheap centrifugal pumps instead of more expensive sub-
mersible pumps. This difference in prescribed pumping technology across a depth discon-
tinuity creates variation in the cost of groundwater pumping that is (assumed) independent
of household wealth. Save for the effect of groundwater access, households just above and
below the threshold would likely have comparable wealth, which addresses the endogene-
ity problem (the association between wealth and groundwater access). Sekhri [2014] use
the depth discontinuity as an instrument (see Section 2.3.1) for groundwater access, and
find that greater depths to groundwater generate higher rates of poverty.

Although rarely used in water resources, RD designs have gained traction in applied
econometrics not only because of their suitability for program evaluation, but also because
the identification approach, which can be represented graphically (Figure 1 c), is particu-
larly transparent. As such, we believe that RD is a promising and under-utilized tool for
causal inference in sociohydrology.

3 Problem 2: Theoretical explanatory power

The empirical tools discussed in Section 2 are promising for causal inference and
statistical prediction in sociohydrology. Specifically, empirical tools help establish unidi-
rectional causality with respect to a large number of different human-water relationships
of interest. While this certainly supports understanding of sociohydrologic dynamics, empiri-
cal approaches alone will not entirely resolve a lack of understanding about the fund-
mental processes that generate sociohydrological system outcomes, nor will they help
explore or simulate coupled human-water system co-evolution directly. For this reason, de-
velopment of sociohydrological theory is valuable. Here, we argue that key insights from
theoretical economics can support development of sociohydrologic theory.

3.1 Challenge: Humans are strategic agents

Traditional hydrologic models have long been extended to incorporate human action
on “small” problems within which causal relations are unique and unambiguous [Siva-
palan, 2015]. Yet sociohydrologic systems are rife with “big” problems, which are wicked,
dynamic and complex [Levy et al., 2016]. Several methodologies from the social sciences
have been adopted (e.g., case-based studies [Mostert, 2018] and agent based models [Berglund,
2015]) to capture complex human-environment interactions in a causal framework. While
these methods may be suitable in many cases for hypothesis testing, these approaches re-
main limited in their potential to support generalizable sociohydrologic theory on their
own because they are often limited by extensive data requirements and concerns related to
the interpretability, falsifiability, and transferability of modeled outcomes [Di Baldassarre
et al., 2015].

In response, some researchers have turned to stylized models, which are general
mathematical formulations that incorporate simplified plausible characteristics of the con-
sidered systems. Stylized models are meant to capture key generalizable dynamics [Di Bal-
dassarre et al., 2015] and provide a flexible and often analytically tractable approach to
modeling human and environmental interactions [e.g., Muneepeerakul and Anderies, 2017].
The general approach is widely used in mainstream modern economics [see, e.g., Sen,
1986], in the analysis of socio-ecological systems [e.g., Anderies, 2015; Yu et al., 2015]
and in water resources management, where human-water interactions are often modeled as
dynamic systems of coupled differential equations [e.g., Mirchi et al., 2012; Madani and
Mariño, 2009; Gohari et al., 2013]. This approach is also taken in sociohydrology, where
human-water interactions are conceptualized as competing feedback loops, representing,
for instance, the tension between the productive drive of society and the restorative abil-
ity of the environment [Sivapalan, 2015]. Human decisions mediate the relative impor-
tance of each loop in driving the full system, and are represented as coupling parameters
in systems of differential equations [Elshafei et al., 2014]. Coupled differential equations were used to model sociohydrologic phenomena including the so-called levee and pendulum swing effects, which have both received substantial recent research attention [Di Baldassarre et al., 2015; Yu et al., 2017; Kandasamy et al., 2014; Van Emmerik et al., 2014]. More recently, human strategic behavior has been incorporated into sociohydrologic models as an additional differential equation representing the ratio of a population that adopts a given strategy [Yu et al., 2017]. This so-called replicator equation is often used in socio-ecologic systems analysis [e.g., Anderies, 2015; Yu et al., 2015]. It arises from evolutionary game theory, a modeling framework in population biology that relates to the principles of non-cooperative games discussed in Section 3.3.1 [Cressman and Tao, 2005].

While the coupled differential equation approach remains fruitful, many water resource paradoxes emerge from what economists refer to as misaligned incentives, which give rise to situations where optimal decisions at the individual level do not aggregate to an optimal system outcome (see, e.g., the groundwater paradox discussed in Section 3.3.1). These effects are not well-represented in coupled differential equation models that do not explicitly incorporate user incentives. Therefore, when considering human decisions in sociohydrologic models, it can become important to not model users as merely replicating successful peers, but rather as fully rational agents acting strategically. Stakeholder decisions must then be modeled as integral and endogenous (i.e. internally-determined) components of the sociohydrologic system.

### 3.2 Approach: Rational Choice Theory

Rational choice theory is a modeling framework that represents economic and social behavior as the aggregate result of individual agents, who each make decisions that are consistent with an underlying preference ranking of all available options. This assumption – the so-called rational choice assumption – is a fundamental principle of modern economics and underlays the game theoretical (Section 3.3.1), political economy (Section 3.3.2) and trade (Section 3.3.3) models discussed in the following sections. It can be shown that under very mild conditions [see Rubinstein et al., 2006], this assumption is equivalent to a scenario in which agents maximize a function representing the utility (i.e., benefit or satisfaction) they expect to generate from the decision outcome. While rational choice is a promising avenue to model endogenous human decision outcomes in sociohydrology [e.g., Grames et al., 2016; Pande et al., 2014], there is substantial debate in the
literature about whether the complex behavior of real humans can be captured by utility
maximization [see, e.g., Sen, 1977; Sivapalan and Blöschl, 2015, in economics and socio-
hydrology, respectively]. Therefore, it is useful to discuss the capabilities and limitations
of the approach for sociohydrology in general, before turning to specific applications (see
Section 3.3). The reader is referred to Sen [1986] for an extended critical discussion of
rational choice.

First, it is important to note that the rational choice framework does not necessarily
imply that agents act selfishly by weighing only personal financial profits (although as a
practical matter, economists often stress self interest as the primary motive in social deci-
sion making [Mullainathan and Thaler, 2000]). Decisions affected by cultural values, like
environmental decisions [Sanderson et al., 2017; Caldas et al., 2015; Roobavannan et al.,
2018], can also be represented by a set of ranked preferences, and are therefore not in-
compatible with the rational choice framework. Altruism, for instance, can be modeled by
so-called "other-regarding" preferences [e.g., Blanco et al., 2011], where utility (usefulness
or benefit to the agent) is not solely determined by personal gain.

Second, it is important to keep in mind that Homo Economicus – an idealized and
perfectly rational agent used by economists to model decisions – does not in fact exist, but
is a lumped conceptual model of Homo Sapiens, in the same way that bucket models in
hydrology [e.g., Wood et al., 1992] are lumped conceptual models of real catchments. Not-
ably, bucket models work in hydrology because self-organization (across space and time)
simplifies the aggregate behavior of complex catchment processes [Sivapalan, 2005]. In
a conceptually similar manner, people tend to self-organize, which gives rise to emergent
behavior at larger scales in sociohydrologic systems [Sivapalan et al., 2012; Sivapalan,
2018]. This suggests that the macro-behavior of sociohydrologic systems can be similarly
represented by a simplified conceptual model capturing key dynamics of human decisions
[Sivapalan, 2018]. In that respect, rational choice stands out as a suitable framework for
modeling human decision-making components of human-water systems, and one that is
easy to comprehend for water resources scientists.

Third, rational choice describes the outcome of decisions as a set of ordered pref-
erences, but does not attempt to resolve the sequence of internal psychological, cultural,
and social processes that give rise to these decisions. Nevertheless, the rational choice as-
sumption does enable relations to be drawn between macro-scale trajectories and specific
characteristics of the environment in which people make decisions (the "decision environment"), rather than individual reasoning. This is useful because decision environments are often easier to address through policy than individual choice. For example, in Müller et al. [2017b], a regulation on the minimal allowable distance between farmers who share groundwater effectively curtailed premature depletion of the aquifer. The regulation recognized that farmers would respond rationally to pumping cost. By forcing a minimum distance between users, the regulation decreased the effect each user had on other users' pumping costs, which decreased strategic incentives to overpump (see Section 3.3.1). This change in the decision environment (the extent to which each user affects others) was arguably more effective in decreasing groundwater overuse than trying to convince individual farmers to alter their behavior.

Lastly, another important feature of the rational choice assumption is its representation using the mathematical formalism of microeconomic theory. This allows for quantitative predictions of system trajectories, which is a key desirable feature of sociohydrologic models. This is not to say that representation of social decision-making using microeconomic principles would allow hydrologists to solve all water management problems through financial (market) incentive or policy mechanisms. In some circumstances, the main insight of using microeconomic theory within sociohydrologic models may well be that the optimal allocation of water resources can not be obtained due to lack of incentives for cooperation [see Pande et al., 2011, for an example].

Obviously, not all human decision outcomes can be explained by rational choice. While the emerging field of behavioral economics [see Mullainathan and Thaler, 2000; Ariely, 2009] allows mathematical treatment of a few specific instances of non-rational behavior (e.g., procrastination [Laibson, 1997], loss aversion [Kahneman, 1979]), most deviations from the rationality assumption have yet to be formalized in a consistent mathematical framework. Economic theory is therefore poorly adapted to situations where non-rational behavior drives the dynamics of the considered system, in which case approaches from qualitative social sciences should be invoked [e.g. Wesselink et al., 2017]. Despite these limitations, microeconomic theory is a rich and parsimonious approach that is well suited to representation of sociohydrologic systems, wherein human decisions affect and respond to the environment. Appropriate representation of the environment is therefore also critical, and with respect to water resources, requires water system expertise unique to hydrologists.
3.3 Applications: Water Resources Paradoxes

In the following section we review literature concerning three water resources paradoxes that have generated substantial research in both the water sciences and economics. For example, literature concerning the paradox of groundwater overuse (detailed further in Section 3.3.1) highlights different perspectives that emerge within the two fields when studying coupled human-water systems: economists and water scientists ask different types of questions and use different types of approaches to answer those questions. On the one hand, economists traditionally associate the phenomenon of groundwater overuse with a common-pool resource problem, where overuse generates negative effects for those who did not choose to experience those effects (cost externalities) [e.g., Gardner et al., 1997]. Economists use game theory to capture strategic incentives that are implicit in the problems that typically arise in common-pool resource systems, however in the case of groundwater, they may oversimplify groundwater flow. In contrast, water resources researchers often consider groundwater to be a resource management optimization problem cognizant of the complexity of groundwater flow [e.g., Gorelick and Zheng, 2015]. However, water scientists may instead neglect misaligned user incentives. Nonetheless, an increasing body of recent research combines both approaches to generate important new insights [Madani and Dinar, 2012; Parsapour-Moghaddam et al., 2015; Müller et al., 2017b]. The example of groundwater overuse from the field of water resources management suggests that sociohydrologists have much to gain from stronger cross-disciplinary interaction with economists when studying coupled human-water systems. Here, we explore specific avenues for collaborations when reviewing the three following sociohydrologic paradoxes: groundwater, water conflicts, and virtual water.

3.3.1 Paradox 1: Groundwater and the tragedy of the commons

Water is a shared resource at many spatial and temporal scales, and water disputes are pervasive [Gleick and Heberger, 2012]. Water disputes often arise from two fundamental features of the resource. First, individual exploitation affects the ability of others to also exploit the resource. For instance, individual pumping affects groundwater elevation and pumping costs for all users, an effect referred to as a pumping cost externality. Second, water flows unimpeded by political and administrative boundaries, making it challenging to prevent water use or contamination by those that do not abide by agreed-upon rules (e.g. within an administrative unit), or follow alternative rules (e.g. outside an admin-
istrative unit). These features (rivalry and non-excludability) are the defining characteristics of water as a common-pool resource and give rise to a paradox (Figure 2(a)), where users acting rationally find themselves in a situation where all parties are worse off.

In effect, a sub-optimal outcome emerges at the system level from the aggregation of individual users acting optimally (i.e., rationally) in anticipation of the choice of others. This emergent behavior can be explicitly captured by game theory, which predicts the state of a system of self-interested, independent and yet interdependent parties. Two broad classes of game theoretical approaches are typically used in water resources applications [see Madani, 2010, a review]. On the one hand, researchers use cooperative games to identify policies leading to desirable (stable, fair, and/or efficient) water allocations among multiple players who are assumed to coordinate and form coalitions when mutually beneficial [e.g., Ambec and Sprumont, 2002; Wu and Whittington, 2006; d’Albis and Ambec, 2010, among others]. On the other hand, non-cooperative game theory does not assume player coordination, but instead models decision outcomes as an equilibrium that emerges from individual utility maximization [Madani and Hipel, 2011]. The non-cooperative framing makes it possible to identify the conditions necessary for agents to collaborate and use shared resources optimally, even when no external actor can be invoked to enforce agreements, as occurs for internationally shared waters (Section 3.3.2) and, in many locations, groundwater.

Because groundwater is a textbook example of common-pool resource [e.g., Ostrom, 1990] that is ubiquitously used but poorly regulated [Megdal et al., 2015], shared groundwater management is the focus of a substantial body of economic research on resource overexploitation (the so-called tragedy of the commons) [e.g., Negri, 1989; Provencher and Burt, 1993; Gardner et al., 1997; Rubio and Casino, 2003; Madani and Dinar, 2012; Saleh et al., 2011; Saak and Peterson, 2007]. While existing studies from economics have outlined important dynamics that drive user incentives, most economic studies consider fictitious stylized cases that are challenging to relate to empirical research from a hydrologic or water resources management perspective. Hydro(geo)logists have a critical role to play in filling this hydrologic process representation gap in at least two regards. First, most previous economic studies heavily idealize groundwater flows, whereas realistic representations of groundwater flows are often critical to understand user incentives. To our knowledge, two existing studies couple high-fidelity (finite difference) numeric aquifer models and game theory [Parsapour-Moghaddam et al., 2015; Müller et al.,
Both studies showed that user incentives are governed by complex groundwater flow patterns that would be missed by simpler models. These effects can have important, and sometimes counter-intuitive, macro-level consequences, as exemplified in the recent agreement between Jordan and Saudi Arabia over the disputed Disi aquifer [Müller et al., 2017b]. Transboundary groundwater agreements are extremely rare, yet Müller et al. [2017b] showed that local flow patterns allowed the unexpected emergence of a new type of agreement that impose buffer zones between well fields, rather than a limit on pumping rates. Violations of this type of agreement are relatively easy to detect, making it a promising approach for improved management of shared fossil aquifers globally. Second, groundwater management studies in economics have shown that uncertainty (e.g. about aquifer characteristics) plays a key role in shaping groundwater user incentives to pump [e.g., Saak and Peterson, 2007]. Understanding the emergence and effect of user uncertainty about groundwater flows is important for understanding why cooperation is so challenging to achieve in shared aquifers.

Figure 2. Selected Water Paradoxes: (a) Tragedy of the commons; (b) Water and Conflicts; (c) Virtual water

3.3.2 Paradox 2: Water and Conflicts across Scales

Despite recurring concerns about ‘water wars’ in media and policy circles [e.g., Barnaby, 2009], the allocation of internationally shared waters is not a significant driver of war between nations [Wolf et al., 2003]. Rather, successful water agreements have opened avenues for diplomacy and regional cooperation [e.g., Kraska, 2009]. Unfortunately, co-
operation dynamics are different within nations, where water scarcity is associated with
civil conflicts [e.g., Gizelis and Wooden, 2010]. A recent stream of empirical studies has
consistently found a significant correlation between climate anomalies (rainfall and tem-
perature) and violence at multiple spatial and temporal scales [Hsiang et al., 2013], par-
ticularly when conflict is related to dependence on agriculture and ethnic fragmentation
[Von Uexkull et al., 2016]. A case in point is the ongoing Syrian conflict, which recent
research suggests is linked to both poor governance and an extreme regional drought [Gle-
lick, 2014]. Hence the paradox of water and conflicts (Figure 2(b)), where water can si-
multaneously be an avenue for cooperation between sovereign states and the object of violent
conflicts between groups and individuals.

While the first component of the paradox – international water cooperation – has
been studied from a wide range of vantage points [see Song and Whittington, 2004; Petersen-
Perlman et al., 2017, for reviews], a number of studies model cooperation as the outcome
of a cost-benefit calculation, where countries act strategically to maximize their own eco-
nomic interest. Non-cooperative games have been widely used in this context as a frame-
work to model the incentives that drive this strategic behavior, and identify conditions un-
der which self-enforced cooperation can emerge [e.g., Rogers, 1969; Just and Netanyahu,
2004; Barret, 1998]. For example, a seminal study using game theory for water manage-
ment focused on transboundary collaboration between India and Bangladesh for flood mit-
tigation in the Ganges [Rogers, 1969]. Yet, the future stability of water sharing agreements
like those in the Ganges, in the context of global hydroclimatological change, remains an
open area of inquiry where hydrologists and economists can collaborate. For example, in a
historical reconstruction of climate and hydrology in two ancient civilizations, Pande and
Ertsen [2014] point to changes in the spatial and temporal variability of climate as shap-
ing the level of institutional cooperation within basins, and found that scarcity triggered
more complex cooperative arrangements. In a theoretical study, Ansink and Ruijs [2008]
showed that while decreasing streamflow can have a destabilizing effect on a river shar-
ing agreement, changes in flow variability can either stabilize or destabilize the agreement,
depending on the particular shape of the streamflow distribution. Discovery of proposed
solutions to such challenges may be aided by use of game theoretical techniques that high-
light cooperative and non-cooperative dynamics. Thus, these studies highlight the capacity
to couple game theory with hydrologic models of streamflow variability to assess water
use vulnerabilities and cooperative solutions in real basins.
The second component of the paradox – why do violent conflicts emerge and persist if they are so costly and destructive? – has puzzled social scientists for decades. In particular, the specific processes, if any, that relate climate variability to conflict are not well established and give rise to intense ongoing academic debates [Hsiang and Burke, 2018; Buhaug et al., 2014; Adams et al., 2018]. In that context, an increasing body of economic literature seeks to identify the conditions that can lead groups or individuals to deliberately choose violent conflict [Fearon and Laitin, 2003; Fearon, 1995; Powell, 2006; Chassang and Padro-i Miquel, 2009; McGuirk and Burke, 2017]. This research concludes that violence can emerge from a trade-off between (i) the current benefits foregone when fighting instead of working, and (ii) the expected future returns of a hypothetical victory [Chassang and Padro-i Miquel, 2009]. Therein, conflicts do not arise from permanent changes in crop yield and water availability (which are associated with income) because foregone benefits and expected returns are both affected: a desertified land is not worth fighting for. However, groups may fight during a temporary drought, because the foregone benefits are low (crops do not grow in the present) and the potential future returns are large (crops will grow in the future). Although simplistic, as institutional and social factors are neglected, these theoretical predictions are consistent with empirical observations of civil wars emerging with climate and income shocks [Burke et al., 2015]. These arguments suggest that a community’s propensity for violent conflict may be affected by the temporal distribution of income, which often relies on fresh water supply and variability. In addition, recent evidence from Syria shows that water resources are also themselves affected by violence, and that this effect propagates regionally along flow paths [Müller et al., 2016]. These spillovers suggest that the consequences of war on water resources can have international repercussions. Thus, climate, water resources, and violence appear tightly intertwined, and hydrologists have an important role to play in clarifying links between them.

3.3.3 Paradox 3: Virtual Water

The notion of virtual water was originally developed to explain the absence of water wars: food imports (and the embedded ‘virtual’ water) was thought to alleviate regional tensions over shared waters by decreasing reliance on irrigation [Allan, 1997]. Under this framework, virtual water flows are conventionally understood to proceed from wet to dry regions according to market forces, and are assumed to lead to more efficient overall use
of water resources [e.g., Allan, 1998]. While this effect arises at the global scale [Chapagain et al., 2006], numerous local exceptions have been documented, where water in comparatively dry regions is used to produce and export food to comparatively wet regions. For instance, arid Saudi Arabia became the sixth largest wheat exporting country in the 1990’s using fossil, non-renewable groundwater [Elhadj, 2004]. Virtual water transfers from (dry) Northern to (wet) Southern China exceeded expected real water transfers in the opposite direction via physical infrastructure (China’s South-North Water Transfer Project) [Ma et al., 2006]. Hence, the Virtual Water Paradox (Figure 2(c)) [Sivapalan et al., 2014]:

Virtual water trade improves global water efficiency but can increase regional water scarcity.

A substantial water resources literature assesses the effect of trade on water availability and food security [e.g., Hoekstra and Hung, 2005; Chapagain et al., 2006; Yang et al., 2006; D’Odorico et al., 2010]. Food trade increases global water use efficiency by allowing (i) crops to be grown in better suited climates with lower crop water requirements [Dalin et al., 2012a], and (ii) ‘blue’ irrigation water in dry regions to be substituted by ‘green’ rainwater in wet regions where there are lower opportunity costs (i.e. lower foregone benefits of not pursuing other uses of available water) [Konar et al., 2012]. However, global trade also allows populations to grow and develop infrastructure and industries that exceed local capacity to meet associated water needs (carrying capacity), which has concerning implications for sustainability and resilience [Suweis et al., 2013]. In addition, because access to trade is determined by the local economy, a small number of (rich) countries have a disproportionate impact on global virtual water flows, which many (poorer) countries rely on for food security [Suweis et al., 2011]. These trading communities evolve over time, and many trade links are created and dissolved every year [Carr et al., 2012]. Due to the strong effect of trade community structures and change on the trade-offs associated with virtual water, a number of studies attempt to identify the factors driving the structure of the trade network [e.g., Tamea et al., 2014; Fracasso, 2014; Tuninetti et al., 2017; Konar et al., 2011; D’Odorico et al., 2012; Suweis et al., 2011; Dalin et al., 2012b, Sartori et al., 2017]. Yet, identification of primary drivers is challenging because variables that represent central features of a virtual water trade system, such as GDP or population, may be simultaneously a determinant and an outcome of trade (see Section 2 for a discussion of causal relationships). Thus, a general equilibrium approach that explicitly accounts for global coupling between trade-relevant variables may be necessary to generate reliable future projections [e.g., Berrittella et al., 2007; Konar et al., 2013].
Concerns about reverse causality (Section 2) are particularly salient when attempting to determine the effect of water availability on food trade because food trade may in turn affect water availability—concurrently or at different scales. Clarifying the relationship between water availability and trade of water-dependent commodities is necessary in order to understand why virtual water can flow from dry to wet regions. Surprisingly, empirical studies in the water resources literature have found little correlation between national water holdings, or endowments, and trade imports [e.g., Yang et al., 2006; Kumar and Singh, 2005]. This is in apparent contradiction with traditional understanding of international trade [Ramirez-Vallejo and Rogers, 2004], where countries specialize in the production of goods for which they enjoy a "competitive advantage" due to their endowment of "production factors", or key inputs to commodity production (e.g. water for food), which benefit the country on a competitive market [Krugman, 2008]. Reconciling this apparent discrepancy remains an open debate. Ansink [2010] argued that water only affects trade decisions if it is the limiting production factor: water abundant (but land-limited) Switzerland imports virtual water. Alternately, Reimer [2012] argued that the discrepancy arises instead from a systematic under-valuation of the opportunity cost of virtual water in food prices. Regions that are water-scarce but rich in (solar) energy to grow crops may have the short term incentive to use non-renewable water resources for irrigation at high opportunity costs. Finally, Verma et al. [2009] notes that the classical trade theory of competitive advantage is not fully supported by empirical observations, even for non water-related goods (the so-called Leontief paradox [Leontief, 1953]), perhaps pointing to deeper theoretical issues to be resolved.

This ongoing debate calls for a closer collaboration between economists and hydrologists to modify existing models so that they provide more realistic representations of international trade as it relates to water resources [see e.g., Eaton and Kortum, 2002, for an example of a trade model that explicitly accounts for geographic features]. A first objective for such collaboration would be to model water as a production factor in a way that accounts for water’s unique characteristics, and thus enable empirical validation. For instance, Lenzen et al. [2013] showed that accounting for the opportunity costs associated with water scarcity substantially affects the modeled structure of the virtual water trade network. Dang et al. [2016] incorporated water-specific features (competition for water between different sectors and climate uncertainty) into a stylized classical trade model to investigate the effect of tariffs and subsidies on water use and food trade. A second objec-
tive of collaboration concerns improving the capacity to make future predictions. While
country-level net food imports matter, food access at household and community levels ul-
timately determines food security. Sen [1981] famously showed that famines rarely arise
from absolute food shortages alone, but rather from the institutions that determine how
food is distributed. These kinds of socio-economic effects are important for water scient-
ists to consider when projecting the evolution of the food trade network. A third objective
would be to resolve associations between virtual water and land use, which are relevant to
conflict. While the general relation between trade and violence is an ongoing debate [e.g.,
Polachek, 1980; Martin et al., 2008; Ansink, 2010; De Angelis et al., 2017], a strong as-
soociation is emerging between virtual water flows and foreign large scale land acquisition
(i.e. land grabbing) [e.g., Rulli and D’Odorico, 2013], which is itself associated with vio-
lence [e.g., Dell’Angelo et al., 2018]. There is scope to combine insights on virtual water
and land use with the wider economic literature on conflict to identify regions and com-
nunities at risk of entering into violent conflict due to virtual water and land acquisition
dynamics.

4 Discussion: Implications for Sociohydrologic Knowledge Generation

In the previous sections we reviewed avenues for water scientists to use tools from
economics and collaborate with economists to jointly address two pressing problems in
sociohydrology: empirical causal inference and theoretical explanatory power. We now
discuss how these insights could be used and combined to address a third, perhaps more
fundamental, problem: the generation of transferable knowledge. Inferring generalized in-
sights from the analysis of specific systems is a well-known problem in hydrology [Beven,
2000]. Hydrologists have addressed generalization by scaling theoretical insights, often
obtained in controlled experimental settings, in models that attempt to predict the large
scale behavior of real catchments [Blöschl, 2006]. Models, and the generalized process
knowledge that they embody, are generally validated by assessing the goodness of fit be-
tween predictions and a sample of corresponding empirical observations [Gupta et al.,
2008]. This approach, which we here refer to as the traditional hydrologic modeling frame-
work (Figure 3 (a)), is severely constrained by the availability of empirical observations,
a challenge that is widely recognized in physical hydrology [Blöschl, 2013]. In sociohy-
drology, the problem is compounded because incorporating humans increases both the
complexity of the system, and the difficulty of collecting the necessary observations (par-
particularly of social processes) to resolve it [e.g., Roobavannan et al., 2017]. In attempting to address the challenge of generating transferable knowledge, sociohydrology appears to have moved organically towards methodological features of modern economic research, which is characterized by a tightly coupled theoretical-empirical interplay, including an affinity for place-based empirical studies that illustrate key dynamics proposed in theory. We have previously argued that causal inference approaches from empirical economics can be leveraged to test hypotheses and generate actionable insights from empirical studies of particular systems (Section 2), and that theory development can support understanding of the fundamental processes that generate those phenomena (Section 3). Next, we discuss the potential to relate theoretical and empirical work in coupled human-water systems in a coherent (albeit not conceptually new) iterative framework intended to facilitate generation of transferable sociohydrologic knowledge from place-based studies.

4.1 Reduced Form and Structural Approaches

To understand linkages between empirical and theoretical work, and how interaction between the two supports transferable knowledge generation, the distinction between ‘reduced-form’ and ‘structural’ approaches in economics [see Chetty, 2009, for a detailed discussion] is useful. Reduced form approaches focus on the relationship between two particular variables of interest from a policy or operational standpoint (e.g., the effect rainfall on runoff, or of climate change on conflicts). These relationships can be estimated through causal empirical inference (i.e., regression analysis, see Section 2), and reduced-form approaches are appropriate for decision support or policy evaluation. However, although broadly consistent with theoretical principles, reduced form approaches do not consider the underlying (and often unobserved) sequence of fundamental processes that give rise to the considered outcome. Theoretical hypotheses, alternatively, are represented explicitly in structural (or process-based) approaches: rainfall affects streamflow through soil moisture dynamics, climate change affects conflicts through income. This is propitious for knowledge generation through hypothesis testing and generalization. This distinction between reduced-form and structural analysis is not directly paralleled in hydrology, but is conceptually similar to the distinction between statistical and process-based models discussed in hydrology [e.g., Müller and Thompson, 2016].

Reduced form (i.e., empirical statistical) approaches for prediction (Figure 3 (b)), are attractive because they have lower data requirements and enable process understand-
ing through their transparency [Beven and Freer, 2001; Chetty, 2009]. However, outcomes of phenomenological studies are inherently place-based, and do not explicitly model processes that give rise to the estimated causal relationship. In other words, while reduced form approaches may determine that, say, rainfall anomalies increase the probability of civil war in Africa [Miguel et al., 2004], they do not determine why people fight following abnormally dry or wet years. Answering the latter question is critical to determining whether climate is related to conflict beyond Africa, and therefore to transferring the findings of the causal empirical analysis to other regions (i.e., generalization). Invariably, this would require explicit theoretical understanding of both human decision and environmental processes. Reduced-form realizations (e.g. case studies) may then be conceptualized as realizations of processes more comprehensively addressed in a structural model. Thus, we argue that a rich interplay between theoretical development and empirical analysis is necessary to understand the mechanisms that govern coupled human-water systems, and model the causal effect of variables that matter.

4.2 An Iterative Research Framework

For sociohydrology, this theoretical-empirical interplay translates to an iterative framework (Figure 3 (c)), where on the theory side, a physical hydrologic model is combined with quantitative behavioral models (Section 3) to inform the development of simplified sociohydrologic models that address specific policy questions. For instance, a microeconomic model can be used to represent the incentives related to income shocks that may cause a farmer to take arms [e.g., Chassang and Padro-i Miquel, 2009], and can be coupled to a parsimonious hydrologic model relating rainfall and land cover to water availability [e.g., Müller et al., 2014]. The resulting simplified coupled model could then be used to generate policy-relevant qualitative hypotheses, for instance on the watershed characteristics that decrease the propensity for conflict. It is important to reiterate that quantitative predictions that might emerge from such theoretical models can typically not be explicitly validated (in the hydrologic sense [Legates and McCabe Jr, 1999]) due to representation of dynamics using unmeasured variables (e.g., utility) or limited data. However, qualitative hypotheses on the statistical significance and causal nature of theoretical relationships can be tested empirically, as discussed in Section 2. Insight obtained from causal analyses of data then informs further refinement of the sociohydrologic model (e.g., new functional forms or inclusion of new variables). The ensuing new theoretical insights
are then tested in a new empirical analysis in another setting, and so on. This iterative framework resonates with recent calls in the sociohydrology community for the development of fundamental understanding of the dynamics of co-evolving human-water systems through iterative hypothesis testing [Troy et al., 2015; Pande and Sivapalan, 2017], rather than a focus on traditional hydrologic forecast [Srinivasan et al., 2015, 2017; Levy et al., 2016; Di Baldassarre et al., 2015].

To be sure, the iterative framework we describe is not new, and flavors of it have been long used to generate knowledge in science, dating back the development of the scientific method. Similar frameworks have also emerged in prior sociohydrologic discussion and research [e.g., Pande et al., 2014; Pande and Sivapalan, 2017; Pande and Ertsen, 2014]. Nevertheless, hydrology has the historical tendency to shift towards the traditional framework represented in Figure 3 (a): a prediction-based paradigm with a high level of fragmentation across processes, places and scales [Sivapalan, 2003; Blöschl Günter, 2006]. For sociohydrology to stay true to its disciplinary vocation to generate and synthesize knowledge on the mechanisms governing coupled human water systems [Sivapalan et al., 2012], sociohydrologists might resist the push to operate within the traditional hydrologic framework. In that regard, the empirical and theoretical approaches from economics reviewed here are important tools for sociohydrologists to consider.

5 Conclusion

Although the number of studies falling under the purview of sociohydrology is rapidly increasing (as seen in special issues in Water Resource Research [American Geophysical Union, 2018] and Hydrology and Earth System Sciences [Sivapalan et al., 2015]), the field is still in its infancy. Its epistemology is in the process of being defined (as seen in the recent series on Debates and Perspectives in Socio-Hydrology, also in Water Resources Research [Montanari, 2015]) and, to date, there is no unified theoretical and methodological framework. To remain relevant, sociohydrology must address the double challenge of making actionable prediction and generating transferable knowledge, while simultaneously bridging important interdisciplinary gaps. This review is motivated by a desire to identify specific analytic tools from economics that can be integrated into sociohydrology’s evolving framework, as well as to inspire similarly focused use of tools from other quantitative and qualitative disciplines to those ends. Our focus on economics stems from its strong
Figure 3. (a) Traditional (Hydrologic), (b) predictive (reduced form) and (c) iterative (reduced form and structural) frameworks for sociohydrologic analysis. The traditional framework (a) requires goodness-of-fit validations with restrictive requirements in terms of data and process knowledge. The predictive framework (b) estimates policy relevant relations using causal inference statistics and observational data, but does not explicitly represent theoretical considerations. The iterative framework (c) incorporates theory explicitly in stylized relations, which generate hypotheses that are tested and updated through empirical causal inference. This framework is propitious to both local policy relevant predictions and the generation of transferable knowledge.

conceptual and technical linkages to hydrology, which suggest great potential for stronger interaction between the two fields.
We propose that advances in sociohydrology will derive from a rich interplay between causal empirical inference and stylized theoretical models, both of which can readily incorporate a suite of economic tools. In the empirical realm, methods for statistical inference in economics, based on natural and quasi-experiments, can be used to distinguish causal relations from mere correlations in complex and data-scarce systems. In the theoretical realm, explicit representation of incentives and strategic behavior, as formalized in economic theory, is often critical to decipher seemingly paradoxical outcomes in sociohydrologic systems. Together, iteration between empirical and theoretical realms can help sociohydrology bridge the gap between process understanding (what scientists do) and prediction (what policy-makers want) that exists in hydrology [Thompson et al., 2013] and economics [Sen, 1986] alike. Importantly, proper understanding of physical flow processes remains essential to addressing most challenges (theoretical and empirical) faced by economists studying water resources and vice versa, and therefore existing approaches from hydrology remain central to any cross-disciplinary work.

Admittedly, interdisciplinary work is not devoid of challenges, which includes poorly compatible academic cultures (e.g., different mentorship expectations, funding mechanisms, and publication goals and desired venues [Levy et al., 2016]). Yet, we believe that basic literacy across the two fields, which can be achieved, for example, by offering economic theory and econometric tools alongside hydrology in interdisciplinary water science education, is critical to advance research on coupled human water systems. This review is an intended first step in that direction.

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