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OPINION PAPER

Prediction in a socio-hydrological world

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ABSTRACT
Water resource management involves public investments with long-ranging impacts that traditional prediction approaches cannot address. These are increasingly being critiqued because (1) there is an absence of feedbacks between water and society; (2) the models are created by domain experts who hand them to decision makers to implement; and (3) they fail to account for global forces on local water resources. Socio-hydrological models that explicitly account for feedbacks between water and society at multiple scales and facilitate stakeholder participation can address these concerns. However, they require a fundamental change in how we think about prediction. We suggest that, in the context of long-range predictions, the goal is not scenarios that present a snapshot of the world at some future date, but rather projection of alternative, plausible and co-evolving trajectories of the socio-hydrological system. This will both yield insights into cause–effect relationships and help stakeholders identify safe or desirable operating space.

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Why prediction is important

Prediction is central to water resources management in planning of both “hard” infrastructure and “soft-path” solutions, such as pricing and conservation incentives (Gleick 2003). Typically, the goal of prediction in water management has been to generate time series of future water availability and use. Water resources scientists and professionals build computer models and calibrate these using historical data to obtain a “working model of the system”. The models are then extrapolated into the future under a range of population, land use, infrastructure, policy and climate scenarios. These are presented to decision makers to help them choose optimal solutions.

Human activities and goals have been an integral part of many water resources system models since the days of the Harvard Water Program in the 1960s (Maass *et al*. 1962). Water resources systems models incorporated human modifications such as dams and canals. Hydro-economic models monetized benefit streams to allow an even-handed comparison among uses (Harou *et al*. 2009) for optimal design and operation. A defining feature of all these models was that the biophysical system was presumed to be relatively independent of the social system in both model development and model use. Two-way feedbacks between water resources and social systems were not usually incorporated. Further, the scientists would typically build models and then hand them over to “decision makers” to make the decisions.

Critiques of traditional prediction

The water sector consists of large, irreversible public investments with legacies lasting from decades to centuries (Thompson *et al*. 2013). Additionally, the need to adapt to a changing climate increasingly involves grappling with predictions 50–100 years into the future (Arnell 2004, Christensen *et al*. 2004). However, typically, these models simply extend approaches used in medium-term planning. They implement long-term climate scenarios while anthropogenic factors such as population, land use, and cropping patterns are extrapolated using simplistic assumptions (Fiseha *et al*. 2014, Palazzoli *et al*. 2015). While conventional water resources modelling approaches have certainly served their purpose for short to medium term planning

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horizons, in the context of *predictions over very long time scales*, they are increasingly being critiqued for several reasons.

First, in conventional predictive models, assumptions about human responses are hard-coded into the model, often by fixing lifestyle choices and societal goals. However, humans have agency: the capacity to think and act independently in response to new information (Fig. 1). Conventional models could help identify desirable future states, but they could not guarantee their attainment because of adaptive responses by humans. As a result, seemingly obvious management decisions have sometimes had unintended consequences (Sivapalan *et al.* 2014). The conventional approach overlooks the fact that water management decisions, both individual and collective, are made within a cultural and institutional context. The cultural and institutional basis from which humans make decisions, comprising social values,[1] norms, beliefs and formal rules, can change in response to environmental and socio-economic conditions and the outcomes of past choices (Ingram *et al.* 1984, Pahl-Wostl *et al.* 2010, Ostrom 2011, Walker *et al.* 2015).

In other words, while human responses may be relatively predictable and "model-able" in the short term, over longer time frames, culture itself may be "state dependent" (Caldas *et al.* 2015). Evolving values, beliefs and norms are manifested through collective action, political shifts, and subsequent changes in formal laws and regulations, which in turn influence how individual actors behave. Multiple case studies show that as societies achieve certain thresholds of wealth, for example, their preferences shift from expanding water use for human needs to environmental restoration (Elshafei *et al.* 2014, Kandasamy *et al.* 2014, Liu *et al.* 2014). Consequently, interactions between water and people result in co-evolutionary dynamics and emergent behaviour (Sivapalan *et al.* 2012, Sivapalan and Blöschl 2015, McMillan *et al.* 2016).

While they are not predictable in the usual sense that hydrologists are accustomed to, as we observe and understand the causes of these emergent phenomena, they can no longer be ignored in long-range predictions and must begin to be anticipated. The same cannot, however, be said about extreme social disruptions such as wars, pandemics, natural disasters, new technologies or social movements that transform the fabric of society in fundamental ways. These so-called "black swan" events (Taleb 2007) are external to water systems; yet if they do occur, they can be expected to permanently alter the trajectories of the water systems (Merz *et al.* 2015, Di Baldassarre *et al.* 2016). While black swan events are inherently unpredictable, we can nevertheless "stress test" predictive models to assess system robustness. For instance, even if we cannot imagine discovery of a rare mineral in an unpopulated

"The computer predicted that I would have a sandwich for lunch. I ate cake!"

Figure 1. Humans adapt to new information including predictions about their behaviour. Credit: Jim Whiting.

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[1] Values, core ideas about right and wrong are at the foundation. These shape people's beliefs about the relationship between humans and the environment, which in turn influence norms about appropriate consequences of action and personal responsibility (Caldas *et al.* 2015).

region that leads to a sudden change in settlement patterns or the removal of a major infrastructure feature such as the Hoover dam, we could still introduce sudden shocks to the model and evaluate new system trajectories from that point on.

Second, by creating information that changes public perceptions, scientists themselves influence shifts in values, beliefs and norms and thus become part of the coupled human–water system (Lane 2014). Water resources modellers have tended to adopt a "loading-dock" model (Feldman and Ingram 2009, Gober and Wheater 2015), which presumes that water resources experts will develop models and hand them over to decision makers to implement. This is increasingly problematic because modellers are not necessarily equipped to imagine new, transformative solutions that have never been attempted before (Gober and Wheater 2015). Furthermore, scientists do not always know what matters to stakeholders. In the loading-dock model, *which* scenarios and processes get modelled have a disproportionately large effect on eventual social outcomes (Troy *et al*. 2015a). There is therefore an inherent conflict in scientists' role in simultaneously predicting the future and shaping it.

For instance, a critique of models of infrastructure projects is that they highlight *aggregate benefits* such as total food and energy production, but not *distributions of benefits and costs* across stakeholders. Frequently, poor, marginalized peoples' interests are overlooked in favour of richer, powerful ones. Political ecologists have long focused on the role of power in shaping the distribution of water resources both within and across scales (Swyngedouw 2007, Molle *et al*. 2009, Sanderson and Frey. 2014). The need to include the concerns of vulnerable groups and also account for the disproportionate influence of more powerful actors is critical to socio-hydrological predictions because inequality is often a key driver of social transitions in water systems (Jackson and Berber 2013, Patrick 2014). In this respect, inequality and power differentials are a particular kind of "feedback" from social to natural systems that would be missed if water users were treated as a single homogeneous group.

Third, place-based studies are increasingly problematic as the traditional unit of hydrological analysis—the basin—may no longer capture geographical "boundedness" in a socio-hydrological world (Konar *et al*. 2016). The rationale for conducting long-term predictive exercises at the basin-scale has been that demand for water is driven primarily by *local* demand for food and domestic purposes. Indeed, indices such as the Falkenmark water stress index (Falkenmark *et al.* 1989) are based on this premise. However, in an increasingly globalized world, local water resources are used to produce commodities that are consumed in distant places (Konar *et al.* 2011). Indeed, reductions in water use in the developed world have been achieved by "off-shoring" production to other countries through imports. Moreover, not only do commodities cross borders but technologies, values, beliefs and norms that underpin consumption and production also have a global reach. These must be considered in water resource system predictions and management.

Prediction over long time scales in a socio-hydrological world

If humans change values, beliefs and norms in response to changing conditions in a nonlinear, seemingly unpredictable manner (Rockström *et al*. 2014), how do we make decisions today that we know will affect future generations for at least 100 years, if not permanently? To make progress in this regard, it seems clear that we need to discard the notion of a value-neutral scientist making time-series projections of water availability for a particular study basin. Instead, we need to explore what managers need to know to help them make strategic decisions that have long-ranging implications. Water managers do not necessarily always need quantitative, probabilistic distributions of water demand and supply for a particular time slice (Bai *et al.* 2016), as we have tended to assume. Rather, for long-range strategic decisions they need to know what portfolios of options exist, how actors will respond to them, what welfare consequences they will have, for whom and over what time frame. They need to know which decisions are irreversible and how to incorporate new information as it becomes available to make adaptive decisions (Sivapalan and Blöschl 2015).

To address these goals, we need to fundamentally rethink the very purpose and concept of predictions over long time frames. We argue that in a socio-hydrological world, predictions are not mere sets of scenarios that present snapshots of the world at some future date, but rather alternative, plausible and co-evolving trajectories of coupled human-water systems, that give insight into possible path dependence, adaptive responses of human actors, tipping points and lock-in situations.

Collectively, these trajectories map out the future *possibility space* (Fig. 2) of the socio-hydrological system (Sivapalan and Blöschl 2015). Different sub-spaces of the possibility space would correspond to different path-dependent technology or governance trajectories. Socio-hydrological models may reveal under what changing circumstances a lock-in situation may

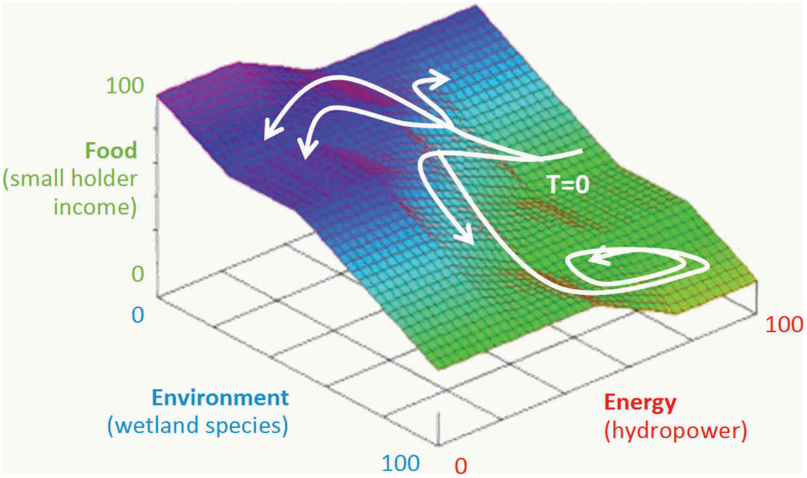

Figure 2. Trajectories illustrating the future possibility space.

develop, i.e. sub-optimal management strategies arose due to path dependence built into the prevailing governance structure (Ceola *et al.* 2016). For example, instituting a groundwater and surface water rights system early in places where groundwater exploitation has not yet begun might result in a very different set of trajectories compared to instituting such a system in a more mature economy.

The goal is then high-level adaptation planning to foreshadow *which sets of actions by which actors* will allow the system to stay within a safe operating space (Rockström *et al.* 2009, Scheffer *et al.* 2009). The kinds of predictions that these models can deliver are a far cry from the calibrated, place-based water resource system models of the past. In the following sections, we demonstrate how each of the above critiques can be addressed, and how socio-hydrological models can be used in strategic water management decisions.

Comparative analyses, generic and stylized models

Socio-hydrological models account for adaptive responses by different actors and thus have the ability to exhibit unexpected, emergent behaviour. But they are challenging to develop. Conventional water resources models are popular for a reason: modellers know how to model the past; they can use observed historical data to calibrate and validate their models. In contrast, in the case of coupled human–water system models, modellers are not yet equipped to anticipate adaptive responses of different actors to future infrastructural, social or policy changes. Harmonizing models of social, economic and natural systems, while taking into account fundamental difference in the models' complexity, scales of dominant processes, requirements for data, evaluation of their performance and applicability of the models for what they intended, remain major challenges. Several recent review papers have documented the challenges involved in socio-hydrological modelling and have offered typologies and approaches to overcome them (Sivapalan and Blöschl 2015, Troy *et al.* 2015a, 2015b, Blair and Buytaert 2016, Di Baldassarre *et al.* 2016).

One approach to the modellers' "tunnel vision" problem about social feedbacks is to learn from other regions through comparative studies and synthesis. Meta-analyses have been used to classify emergent phenomena and trace their causes (e.g. syndromes in Srinivasan *et al.* 2012). Comparative case study research has been used to articulate trade-offs and unintended consequences (e.g. irrigation efficiency paradox in Scott *et al.* 2014, or peak water paradox in Sivapalan *et al.* 2014) in ways that could help modellers envision adaptive responses of actors. Comparative research allows modellers to set out a technology/policy road map, and then examine their implications by analysing other similar cases. For instance, under what conditions may water reuse gain social acceptance, and how would a road map that includes this option evolve?

Another approach has been to build generic socio-hydrological models that aim to replicate emergent phenomena observed in multiple locations (e.g. the levee effect in Di Baldassarre *et al.* 2015 and the pendulum swing in Elshafei *et al.* 2014). These models provide valuable insights into socio-hydrological dynamics. One problem is that the gap between these models and "on-the-ground" decision-making limits their practicality (Sivapalan and Blöschl 2015). Elshafei *et al.* (2016) offer a middle ground by applying a generic model to a real-world study site (the Lake Toolibin catchment in Australia). The authors then evaluate the sensitivity of catchment trajectories to both internal structure and the external socio-political context. Here it should be clarified that the goal is not to create a "model of everything". No model can represent culture, environment, technology, demography, economy and governance in quantitative terms under all conditions. Model scope must still depend on the types of policies and future conditions the model aims to evaluate (Garcia *et al.* 2016).

Facilitating stakeholder participation

If water resources modellers can shape social futures they must accept the responsibility that comes with it by facilitating stakeholder participation. Including stakeholders in the modelling process can ensure ownership of model results and the decisions that follow (Sivapalan and Blöschl 2015, Walker *et al.* 2015). Socio-hydrological models that clarify stakeholder values and beliefs can be used as tools for conflict resolution and negotiated solutions because they highlight where conflicts arise from *differences in values* and *difference in beliefs* about how the system behaves.

Facilitating formal participation requires investments in better communication as well as building credibility and legitimacy (Dilling and Lemos 2011, Gober and Wheater 2015). Participatory, collaborative (Guldan *et al.* 2013) modelling is already being used to facilitate public participation in integrated water resources management (IWRM). A range of tools, such as role play, serious gaming (Voinov *et al.* 2016) and decision theatres (White *et al.* 2010), exist that can be adopted in socio-hydrological modelling to elicit values, beliefs and norms, understand actor responses to different environmental states and also educate them about the biophysical implications of their actions. However, building useful models does not necessarily have to involve formal stakeholder interactions; reference to contemporary debates can also be used to identify salient questions and thus the scope of the model (Srinivasan *et al.* 2015, Garcia *et al.* 2016). If the goal is to explore outcomes that are useful, socio-hydrological modellers must be willing to go out on a limb and seek unconventional data at the scale and granularity needed. Hitherto, water resources modellers have focused on variables that are easy to model rather than what matters. For example, they may simulate streamflow at a gauging station, whereas stakeholders may care about fish populations or upstream–downstream inequity. Absence of data is often the barrier in developing salient models. To overcome this, modellers should target data collection efforts to address the most critical knowledge gaps and explore new data sources: big data, citizen science, participatory monitoring, new sensing technologies or satellite data products (Buytaert *et al.* 2014).

Linking local and global scales when appropriate

Research linking global virtual water trade to the basin scale is nascent. Most virtual water trade research has focused on international trade between countries (e.g. Konar *et al.* 2011), partly constrained by data availability. However, recent research has begun to evaluate sub-national virtual water transfers (Dalin *et al.* 2014, Dang *et al.* 2015), including those to and from cities (Rushforth and Ruddell 2016), and these studies suggest that hydrological units such as the basin may not always be the appropriate scale at which analysis/prediction is possible. On the one hand, local water scarcity may not significantly impact global markets unless the region contributes to a substantial fraction of global production. For instance, aquifer depletion in the USA could potentially influence global grain markets due to the magnitude of the US crop production (Marston *et al.* 2015). On the other hand, a more pressing challenge is addressing how global markets influence demand for water in water-scarce regions.

More synthesis research on the strength and nature of couplings between different basins and global markets is needed to inform to what extent and how global forces must be incorporated into basin models. Based on existing meta-analyses (Srinivasan *et al.* 2012), we suggest that the degree of coupling with global markets and consequently the modelling approach adopted are likely to vary depending on the factors that limit current water use. The coupling is likely to be weak where agricultural water use is limited by other production factors (e.g. land scarcity as in Singapore, or sunlight as in Canada) or by water policies. Urban or industrial demand could still increase; but as long as water abstraction is tightly controlled (either directly through water rights/licences or indirectly through environmental protection laws, such as the US Endangered Species Act), demand for urban or industrial water uses will likely be met by reallocation from agriculture rather than over-allocation. In contrast, in many emerging economies in the semi-arid global south, land and sunlight are not limiting factors. Moreover, controls over abstraction are also weak. In these regions, water use is largely limited by investments in irrigation. As a result, withdrawals could increase sharply as their economies grow. The influence of global demand could be considerable in the long term and must be taken into consideration. In cases where the coupling is strong, modelling may be done analytically (Dang *et al.*

2016) or numerically by incorporating market prices exogenously as time-varying boundary conditions (Elshafei *et al.* 2016).

Summary

Water resource management involves large public investments with long-range impacts that traditional prediction approaches cannot address. These are increasingly being critiqued because: (1) there is an absence of two-way feedbacks between water and society; (2) models are created by domain experts, who hand them to decision makers to implement; and (3) there is a failure to account for the interaction between global forces and local water resources. Addressing these critiques requires a fundamental change in how we think about prediction, particularly in systems where social dynamics dominate the change.

In this article, we have offered three specific changes needed to improve hydrological predictions. First, we suggest that in the context of very long-range predictions, the goal is not to generate scenarios that present a snapshot of the world at some future date, but rather alternative, plausible and co-evolving trajectories through the use of socio-hydrological models. Second, these models must try to simulate outcomes society actually cares about, so they can facilitate stakeholder participation and steer societies onto better trajectories. Third, in an increasingly globalized world, models must account for broader economic, social and cultural influences on the system of interest.

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