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On the role of individuals in models of coupled human and natural systems: Lessons from a case study in the Republican River Basin

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ABSTRACT

In models of coupled human and natural systems (CHANS), the role of individuals and human behavior is often overlooked as data are scarce and assumptions hard to verify. To assess this role, we couple an agent-based model simulating farmers' behavior and a groundwater model and apply the models to the case of groundwater-fed irrigation in a river basin in the High Plains Aquifer region. Results show the crucial role of human behavior in driving the interactions between these coupled systems. Conversely, individuals are impacted by the systems' dynamics in different ways depending on physical, economic and social characteristics. The findings provide implications for local policy making and education and demonstrate that assumptions on human behavior could be treated as an additional source of uncertainty. This work suggests that modeling individuals and human behavior can be an important step to simulate and understand the dynamics of CHANS in a holistic way.

1. Introduction

Climate change, deforestation, disappearing lakes and seas and other large-scale environmental issues, such as the hypoxia zone in the Gulf of Mexico, demonstrate that the Earth has moved into the Anthropocene: an age where humans are the main driver of environmental and ecological changes (Crutzen, 2006; Steffen et al., 2011). This realization has prompted scientists to create a new form of science focusing on coupled human and natural systems (CHANS). This science has been growing steadily over the past 15 years (Liu et al., 2007; Alberti et al., 2011) and advocates for integrated assessment of human and environmental systems. There have also been a number of frameworks and sub-fields that have emerged in this area to study specific CHANS such as socio-hydrology (Sivapalan et al., 2012), social-ecological systems (Schlüter et al., 2012), hydro-economic systems (Cai, 2008; Harou et al., 2009), integrated environmental modeling (Laniak et al., 2013) and others. The science of CHANS calls for interdisciplinary collaboration and systematic modeling of both human and natural systems to reveal the complex dynamics at stake in such coupled systems.

Models of CHANS are designed to integrate both human and environmental dynamics in order to analyze the co-evolution of human and natural systems (Gual and Norgaard, 2010; Laniak et al., 2013). In the past few decades, environmental models have become more and more complex due to improved computing power and improved quality of data, both spatially and temporally. The inclusion of the human component in environmental models is a more recent effort which is still in its infancy. While progress has been made and new tools have been adopted to develop more integrated environmental models (Kelly et al., 2013), much challenging work is still needed to properly represent human behavior and human influence in these models (An, 2012). One of the main challenges is the validation of such models due to the lack of data and understanding of human behavior (An, 2012; Ligtenberg et al., 2010). Moreover, little is known on the effects of human activities to the performance of complex systems such as watersheds or river basins and very few studies have systematically evaluated the impacts of complex human behavior on CHANS (Huang et al., 2013).

It is often not straightforward to decide what model to use for a human system. Various tools have been developed in social sciences (Lave and March 1993), economics (Tesfatsion, 2003), psychology (Gluck and Pew, 2006) and other fields but no model has been universally accepted across all disciplines as the best way to model human behavior. One modeling approach however has

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been regularly cited as being particularly effective for simulating CHANS: agent-based modeling (ABM). An (2012) provides a review of agent-based models (ABMs) used to model human decisions in CHANS, which identifies 121 publications applying ABM to CHANS as of 2011, mainly in the fields of ecology and geography. Kelly et al. (2013) identify ABM as one of the five most common approaches that have been used for integrated environmental assessment and management. In the field of social-ecological systems the use of ABMs is particularly prevalent, as illustrated by Rounsevell et al. (2012), Schlüter et al. (2012) and Filatova et al. (2013). ABMs have also been used to study agricultural and water resources systems by modeling different types of water users such as domestic users (Athanasiadis et al., 2005; Galán et al., 2009), water users in river basins (Schlüter and Pahl-Wostl, 2007; Yang et al., 2009 and Yang et al., 2011), irrigators (Arnold et al., 2014; Berger and Troost, 2014) and farmers (van Oel et al., 2010). These studies show that ABM is a promising, and in some fields well-established, tool to study the interactions between humans and the environment.

Managing water resources systems is usually incredibly difficult not only because of the variability and uncertainty related to climate and hydrology, but also because of the uncertainty and variability related to water demand. The study of individual behavior is particularly important in the field of water demand management. Most water resources systems are dedicated to individuals that need water such as household owners, farmers, fishermen, or users of recreational bodies of water. Understanding these users is therefore a key component of sound management and policy, especially when water is scarce and conservation becomes a major concern. Jorgensen et al. (2009), for example, present an integrated model to better understand household water use behavior. They find that interpersonal and institutional trust are crucial factors of household water consumption behavior, even though such behavioral characteristics of individuals are overlooked in most studies. Russell and Fielding (2010) go even further by studying the psychology of water users in order to understand water conservation behavior. They identify five causes of residential water conservation behaviors: attitudes, beliefs, habits or routines, personal capabilities, and contextual factors. These two examples illustrate the importance of understanding individual behavior to study water demand patterns so as to devise better policies for water conservation. What is true for residential water management holds for irrigation management too. Irrigation varies in space and time and from farmer to farmer. Sauer et al. (2010) show that irrigation development and practices have impacts even at the global scale.

Few studies have shown the role of individuals in CHANS, especially when these studies were designed for water resources systems analysis (An, 2012). Our study is an attempt to understand how individuals matter in modeling CHANS and what can be learned from modeling the human system at the individual level. We address these questions using an integrated ABM and a groundwater model. It should be noted that it is not necessary to use an ABM to simulate a CHANS, as one could focus on the properties of the system, where the microscale interactions may not be important for the study purpose, as seen in many modeling efforts (Laniak et al., 2013). Under some conditions implementing an ABM is not feasible, especially when data required for modeling individuals are hard to obtain because of ethics or other reasons preventing data collection (Filatova et al., 2013). In this paper, we choose to use an ABM because it is a natural framework to model individuals, especially human agents in the human dimension of CHANS. The heterogeneity of the individual behaviors affects the emerging performance of the system. In the ABM, individual farmers are defined as agents who make daily decisions on groundwater use to irrigate cash crops and earn profits. The ABM also includes an agent representing a regulatory agency that monitors water levels and implements water-conservation regulations. The human behavior of an agent is considered as a variable in the ABM. Human behavior heterogeneity is an important characteristic of water users in general although it is difficult to measure and quantify. Two farmers with crop fields in the same physical conditions (i.e., soil type, climate, well yield, etc.) could still make different irrigation decisions following their experience, their perception of risk and other factors. Among the studies of agent-based models on agriculture and agricultural water management issues, Berger (2001) introduced diversified technology adoption behaviors among farms, and using a human behavior parameter on the various thresholds to technology adoption to quantify the human behavior heterogeneity associated with physical heterogeneity of farms. A more recent study by Baggio and Janssen (2013) tested various behavioral theories (i.e. with experimental data of irrigation games). For a review of relevant studies with more detailed discussion on human behavior representation in an ABM, readers should refer to Kremmydas (2012) and Elsawah et al. (2015).

In this framework, farmers and institutions form the human component of the system, rivers and the aquifer form the natural component of the system, and the two coupled systems interact through irrigation, water conservation, and regulations with influence of external factors such as climate and crop market. We show that these two models coupled together and validated for in a watershed of the Republican River Basin (RRB) in Nebraska illustrate the importance of including individuals and human behavior in modeling CHANS. It is important to note that researchers working at the individual level may need to consider ethical integrity when any non-publicly available data are used.

Our work is related to several recent studies, which share a similar context (i.e., connecting agriculture, economics and groundwater) and modeling approach with ours. Castilla-Rho et al. (2015) developed FlowLogo to help researchers develop coupled agent-based groundwater models. It is an interactive modelling environment that allows users to explore how patterns of groundwater movement and social development can emerge from agents' behavior and their interactions. Bulatewicz et al. (2010) use the Open Modeling Interface to integrate models of agriculture, economics and groundwater and applied the methodology to Sheridan County in Kansas located above the High Plains Aquifer. Condon and Maxwell (2014) present an integrated hydrologic model to study the spatial and temporal patterns caused by feedbacks between irrigation and water availability in the Little Washita Basin in Southwestern Oklahoma, USA. Foster et al. (2014) introduce a new modeling approach of irrigation behavior in groundwater systems. Their modeling approach incorporates the impacts of well yield and climate on crop production and water use to determine irrigation demand. Mulligan et al. (2014) present a model which couples an agent-based model of farmers' irrigation behavior with a groundwater model to study a subwatershed of the RRB. We share a similar modeling approach or have a similar study area as these four studies, but what makes our work unique is that we assess the importance of individuals and their behavior in modeling CHANS.

In the rest of this paper, the modeling framework is presented in section 2 and its application to an area located in the RRB is presented in section 3. Results are then described and explained in section 4. Additional discussion on the importance of representing individuals in CHANS and conclusions are provided in section 5.