Mechanistic coupling of social and biophysical models of water management through agent typologies

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Abstract

Modeling the coupled social and biophysical dynamics of water resource systems is increasingly important due to expanding population, fundamental transitions in the uses of water, and changes in global and regional water cycling driven by climate change. Models that explicitly represent the coupled dynamics of biophysical and social components of water resource systems are challenging to design and implement, particularly given the complicated and cross-scale nature of water governance. Agent based models (ABMs) have emerged as a tool that can capture human decision-making and nested social hierarchies. The transferability of many agent-based models of water resource systems, however, is made difficult by the location-specific details of these models. The often ad-hoc nature of the design and implementation of these models also complicates integration of high fidelity sub-models that capture biophysical dynamics like surface-groundwater exchange and the influence of global markets for commodities that drive water use. A consistent, transferable description of the individuals, groups, and/or agencies that make decisions about water resources would significantly advance the rate at which ABMs of water resource systems can be developed, enhance their applicability across ranges of spatiotemporal scales, and aid in the synthesis and comparison of models across different sites. We outline here a framework to systematically identify the primary agents that influence the storage, redistribution, and use of water within a given system. Reviewing previous studies that apply ABMs to water resources, we propose eight water resources agent types that capture the operational roles that modify the water balance. This typology characterizes common actors in water management systems but can be modified to represent the particularities of specific systems when more detailed information about specific actors is available (e.g. social networks, demographics, learning and decision-making processes). Application of the proposed typologies will support the systematic design and development of transferable scaleable water resources ABMs and facilitate the dynamical coupling of social and biophysical process modeling. To demonstrate, we show the conceptual development of an ABM that describes the interaction of agents within the Boise River Basin in the western United States and illustrate how those agents interact with the biophysical system.

Keywords: water resources management, agent-based modeling, social-ecological systems, socio-hydrology

1 Introduction

Humans are affecting the availability and quality of water resources across scales ranging from local to global. The spatiotemporal distribution of freshwater influences and is influenced by human decisions about distribution of water across scales, creating a multiscale, dynamically coupled natural-human (CNH) system. Globally, water withdrawals are increasing (2500 to 4000 km yr-1 from 1971-2010), but sectoral trends in water withdrawals vary across regions for a variety of reasons, including increasing water use efficiency, population growth and urbanization (Huang et al., 2018). Meanwhile, the availability of water impacts a range of societal decisions such as where to build and how to insure structures in floodplains, the type of crops to plant, water use restrictions in urban areas, trans-boundary water transfers, and infrastructure development (Dubbelboer, J., Nikolic, J., Jenkins, K., Hall, 2017; Ahmad and Prashar, 2010; Sehlke and Jacobson, 2005; Jeuland et al., 2014). Globally, owing to the intensification of the global hydrologic cycle (Huntington et al., 2018) anthropogenic climate change has altered the frequency and intensity of precipitation and will continue to do so (Bates et al., 2008). Determining how climate change will affect this multiscale CNH system will be critical to assess potential adaptation strategies.

Hydrologic models that explicitly consider two-way interactions of humans and the biophysical environment has taken form as system dynamics models (Sehlke and Jacobson, 2005; Ma et al., 2007; Schenk et al., 2009) and hydro-economic models (Michelsen et al., 1999; Esteve et al., 2015; George et al., 2011). These models have emerged from a longstanding interest in integrated water resources management (Petak, 1980), which has promoted a holistic approach to water management that seeks to balance the competing needs of stakeholders within environmental constraints. Recognizing the importance of enhancing fundamental understanding of and the ability to model these systems, a growing subdiscipline of socio-hydrology, which focuses on the co-evolution of coupled human-water systems, has received increasing attention (Sivapalan et al., 2012). This subdiscipline can be distinguished from integrated water resources management insofar as it is explicitly exploring human responses to hydrologic events such as relocating or building levees after flooding (Di Baldassarre et al., 2013; Van Emmerik et al., 2014). Advances in the theoretical underpinnings of socio-hydrology have paralleled corresponding advances in social-ecological systems modeling, which presents a framework to determine the trajectories of CNH systems by integrating models of human behavior and decision-making with biophysical models of the environmental systems in which they are embedded (Ostrom, 2009).

Although these types of integrated models are becoming more common, there are ongoing challenges with respect to synthesis across systems, scaling across nested levels, and integration of various sub-models that represent key biophysical processes with high fidelity. Some of these challenges have been addressed within the hydrologic sciences through efforts such as the Community Surface Dynamics Modeling System (Peckham et al., 2013; Overeem et al., 2013), and other model coupling frameworks (Khan et al., 2017; Tidwell et al., 2001). Additionally, social theory has generally been underutilized in these integrated models, but agent based models (ABMs) are a promising tool to reflect the complex social interactions between individuals and organizations across scales.

ABMs are an increasingly popular class of models that are capable of explicitly capturing the dynamic feedbacks and cross-scale components of a CNH. Current ABMs focused on water management are often created in an ad-hoc fashion due to highly specific, place-based questions. This leads to a highly variable representation of individuals or hydrologic components across systems. Within the social sciences, various typologies have been created to abstract the recurrent or repetitive aspects of agents (Mckinney, 1950). Because typologies are not expected to be an exact representation of individuals, they can be a valuable heuristic tool and provide a basis for comparison across systems. These standardized classifications serve the model building enterprise by identifying the features of individuals influencing water resources and the associated hydrologic variables they affect, thus making modeling these systems more consistent and comparable.

Agent functional types (AFTs) have been proposed as an additional way to increase transparency of agent representations, and simplify model development (Arneth et al., 2014). Functional types define agent roles, attributes and behaviors, as well as social networks, imitation, and learning (Arneth et al., 2014). AFTs are analogous to plant functional types in that they can represent consistent individual responses to and influences on systems across large geographic extents (Arneth et al., 2014). Previous studies that have used AFTs as building blocks in ABMs have defined characteristics of various land owners, such as farmers (Valbuena et al., 2008; Dalolu et al., 2014) and forest owners (Blanco et al., 2015). AFTs have been used to analyze land use planning at the international scale (Blanco et al., 2015, 2017,), determine how policy interventions affect spatial patterns of conservation practices (Dalolu et al., 2014), and have improved the clarity and flexibility of ABMs in ways that might increase the use of these models for planning and policy-making (Valbuena et al., 2008). For example, Blanco et al. (2017) found that the behavioral attributes of different forest owner types more significantly impacted profit and therefore land use dynamics than climate change alone. Importantly, these behavioral attributes influenced how different owner types managed their forests in response to societal demand for particular ecosystem services. In the context of water resources management, the use of AFTs could also lead to important insights about the emergent dynamics and path dependency of social-environment interactions. However, the hierarchical and cross-scale nature of coupled human-hydrological systems necessitates first creating a broader framework for capturing the diversity of water management actors.

Here we propose a typology for water resource management actors that can facilitate more transparent, transferable, and comparable ABMs of water management systems. Our agent typology is based upon a review of 42 published studies that apply ABMs to water resource systems. From these prior studies we identify common water resources agent types across systems, define their operational roles, associated input/output variables, and potential social interconnections. The typology is useful because the agent types allow expedited identification of agents to include in coupled water resources models, aid in the representation of nested social and institutional structures, simplify coupling with component sub-models, increase the transferability and synthesis of models across systems, and potentially enable development of regional scale CNH models of water resources. This broad agent typology would lay the foundation for more specific functional types to be developed within each type of agent (e.g. farmer and forest AFTs Valbuena et al. (2008); Blanco et al. (2015)).

The remainder of the paper is organized as follows. First, we review current methods and challenges in modeling CNH systems. We then provide an overview of the literature review we conducted in developing this framework. We then outline the definitions of each agent type, associated biophysical and social interactions, and information that might influence modeled decision-making processes. And finally, we provide an example of how this framework would be used to develop an ABM of a coupled human-hydrologic system in an arid watershed in the Western US.

2 Modeling Water Resources as a Coupled Natural-Human System

Analyzing and modeling water resources systems as explicitly CNH systems is receiving increasing attention in the literature. But methodologically these efforts are often isolated along traditional disciplinary boundaries that present unique strengths and important limitations (Table 1). For example, system dynamics models and optimization schemes have been the basis for many decision-support tools meant for participatory modeling and watershed management (e.g WEAP, Yates et al. 2005; RiverWare, Zagona et al. 2001). These are important tools that typically focus on applied scenarios. In contrast, socio-hydrology has focused on the co-evolution and behavior of coupled socio-hydro dynamical systems with the goal of advancing our fundamental understanding of how systems work and evolve. Hydro-economic modeling integrates economics with management options and infrastructure development and maintenance, and generally assumes that individuals have complete knowledge and make rational decisions (e.g. net benefit maximization, Harou et al. 2009). As an example of how the use of agent typologies in ABMs can simplify representations of individuals and their decision-making processes, we focus on system dynamics modeling as an overarching integrative tool for coupling agent based models (ABMs) with biophysical models.

System dynamics modeling is particularly suited for quantifying the complex feedbacks and relationships between sub-systems (for a comprehensive review see: Nikolic and Simonovic 2015; Mirchi et al. 2012), but these often represent simplified versions of system components which do not necessarily include process-based components. Although institutions and individuals may be included in these systems models (e.g. Schenk et al. 2009; Rehan et al. 2013), they often lack depth and specificity in regard to social interactions and decision-making processes. Likewise, models that have been used in socio-hydrology have calibrated variables that are not directly linked to social theory and can omit important individual-level characteristics of decision making (e.g societal awareness Van Emmerik et al. 2014, psychological shock in Viglione et al. 2014). On the other hand, some models that represent realistic human actors simplify the hydrologic dynamics by using hypothetical or average hydrologic conditions (Woyessa et al., 2011; Cai and Xiong, 2017) or completely omit important processes (e.g. surface water-groundwater interactions). The challenge of representing each subsystem with a high degree of fidelity has promoted the use of multi-method models which use systems perspectives to combine process based models of the biophysical environment and agent based models that represent the socio-economic environment (Nikolic and Simonovic, 2015).

Agent based models (ABMs) are increasingly being used for CNH system modeling because they can represent the dynamic feedbacks between human and environmental systems. Agents represent individuals, collections of individuals, groups, or organizations that make decisions based on responses to stimuli either in the environment or among other agents with whom they interact. Because agents may respond conditionally to combinations of stimuli, this allows ABMs to represent heterogeneous sets of agents that reflect the range of perceptions, beliefs and socio-economic status of the population of interest. Agents possess adaptive behavior and can utilize various decision-making mechanisms. ABMs allow us to identify cross-scale, dynamic, and emergent system behaviors (agents impact system, system influences agent behavior, Wilensky and Rand 2015). ABMs are valuable because they can represent network heterogeneity, local but complex interactions, and unequal distribution of information sources (Wilensky and Rand, 2015). This is a particularly useful tool for water resources management due to the ability to represent cross-scale components of systems and institutional hierarchies where higher representative units could be used in a nested approach (Rounsevell et al., 2012). For example, agricultural agents water rights could be represented as individuals, or as irrigation organizations which own water rights and ensure delivery to their users.

Typologies can represent the operational roles of individuals or organizations and are the top level in a nested structure, where an agents' role(s) define how they interact with each other and the biophysical system. For water resources, a water agent typology would specifically identify how an agent influences the consumptive use or quality of water by directly or indirectly mediating the timing and distribution of water across the landscape. Although the individuals, and the exact structure of these relationships will change across systems, the roles and observational information used by water managers, or individual users will be relatively consistent (e.g. snow water equivalent, forecasted precipitation, groundwater levels, etc.). As such, classifying common types of individuals and institutions mediating the timing and magnitude of water flows will expedite and simplify coupling of models by identifying relevant input and output variables for ABMs.

The water agent typology that we develop here serves as a foundation for classifying agent-functional types. Agent-functional types can synthesize heterogeneity in agent attributes and decision-making strategies. Land-use agent-functional types have been used in this way (Rounsevell et al., 2012), but the approach has not yet been applied to water management, in part because the first step is to develop a clear agent typology, as we produce here. AFTs characterize heterogeneity through agent attributes (e.g. socio-demographic or economic attributes, spatial data such as irrigated acres and crop type) and preference weights associated with agent objectives or desires which guide their decision-making (e.g. preferred management practices Blanco et al. (2015)). Decision-making strategies incorporate heterogeneity and uncertainty in how agents enact their role in the system and could include how they use available information and learn over time. These strategies can be represented by decision trees (heuristics), utility maximization, and bounded rationality, but the practice of including decision-making based on theory has been limited in the land use change ABM literature (Groeneveld et al., 2017). The use of optimization in water resource management is useful for identifying ideal outcomes given specified objectives and constraints. However, capturing the nuances and diversity (e.g., biases, stochasticity) in how decisions are made and propagate through coupled human-hydrologic systems is necessary to identify emergent properties and outcomes.

3 A Classification of Water Resources Agent Types

We conducted a literature review of water resources ABM papers, allowing us to systematically identify common water resources agents using both inductive and deductive approaches. Inductive analyses (such as clustering e.g. Fontaine and Rounsevell (2009)) might use national databases of socio-economic characteristics, or social surveys, while deductive reasoning uses a combination of cultural theory and expert opinion to create a more continuous multi-dimensional categorization (Talbot, 2009; Rounsevell et al., 2012). We used the ISI Web of Science to find water resources ABMs by using the following search terms: water + manage* / typ*; ABM + water; Grimm 2010 and Grimm 2006 with water + agent. Criteria for inclusion of studies into the review was that the ABM was used to assess some water resources issue (theoretical modeling experiments that were not based on a specific location were excluded) and with sufficient model description to characterize agents and associated roles. There were 39 papers included in the literature review, covering locations across the globe spanning the US (7), Europe (9), Asia (9), Africa (6), South America (4), the Middle East (3) and Canada (1). We documented the agents reported in each manuscript and grouped them by the characterization scheme provided by (Akhbari and Grigg, 2015). These agent types included urban/domestic, industrial, agricultural, regulator, environmental, hydropower, and recreation.

Within each agent type we documented associated roles used in each model (Table 2). These operational roles encapsulate the mechanisms by which each agent type influences water quality or quantity in the system. After reviewing the roles of each agent type we modified the (Akhbari and Grigg, 2015) classification scheme in regard to three of the agent types. First, rather than having a functional type that specifically represents hydropower generation we broadened the scope to include all dam managers. This enables representation of individual dam operation objectives through attributes of a given dam manager. Secondly, we grouped environmental and recreation agents into an interest group agent. These various agents have a specific role of communicating a range of desires from constituents to regulatory agents. We also added two new agent types, utilities and economic agents because they were used in numerous ABMs and represent specific roles further defined in section 3. Our final agent types include: agriculture, regulatory, domestic, industrial/commercial, utilities, interest groups, reservoir managers, and economic agents.

The most common agent types found in the literature were irrigators, regulators, and domestic users, present in 32%, 21% and 16% of papers respectively (Figure 1). In the following sections we define the role of each agent type, specify at what scale and at which point(s) in the biophysical system they act, how and to what extent they communicate with other agents (Figure 2), and identify the type of information they use in decision-making and potential attributes that might influence those decisions. We then highlight research gaps and future work that could build on research in the literature review.

3.1 Agriculture

The role of the agricultural agent is to withdraw water from the system, distribute and apply it to the landscape through irrigation.

These agents main role is to withdraw water from the system either from surface or groundwater for irrigation purposes (Table 2). They can also create and maintain structures that transport water to agricultural areas (e.g. canals), add new groundwater wells and irrigation systems (Becu et al., 2003), buy and import water (Barthel et al., 2008), and adopt innovations such as irrigation or pumping technology that directly impact their consumption of water (Holtz and Pahl-Wostl, 2012). The agricultural domain is one of the most commonly used functional types in water resources ABMs (Figure 1).

3.1.1 Biophysical Interactions

Agricultural agents operate across scales, representing individual farmers or irrigation districts. Higher-level organizations, such as water districts can control the distribution of water to canals, ditches, pumps and facilities diverting water (IDWR, 2018). Agricultural agents have a direct influence on stocks and flows of water; at the largest scale they divert water from rivers into extensive canals which results in evaporative losses, and leakage into the shallow groundwater table. At the individual scale, agents determine how many acres to irrigate, and the quantity and source of water to use, thereby effecting evapotranspiration and return flows across large areas. Their role in the biophysical system also has significant impacts on carbon and nitrogen cycling and associated water and soil quality.

3.1.2 Social Interactions

Agricultural agents make decisions using information from a variety of sources, including family members, personal expertise, farmers' associations, neighbors, research institutes, private consultants, or the internet (Karali et al., 2013; Barbalios et al., 2013). Their social networks can influence individual interactions and knowledge sharing about irrigation technologies and conservation practices. Farmers and irrigation districts can share information regarding timing and quantity of water to deliver. Irrigation districts can be the interface between farmers and the individual who manages water distribution who is often overseen by the regulator agent (Becu et al., 2003; Berger et al., 2007; IDWR, 2018).

3.1.3 Decision - making

Agricultural decisions are a function of individual incentives, transaction costs, institutional rules, and interactions between local users and higher-level irrigation agents. As such, both individual decision-making and social dynamics influence the use and distribution of water in a system as impacted by agricultural agents. Agricultural agent decision-making would then be based on values related to profit, history, new technology, and loss aversion (Table 3). For example, profit would be based on forecasted yield of a given crop, and history would characterize decisions made in the previous time steps (e.g. they grow three crops in rotation). Adaptation of new technology could be based on information exchange with other agricultural agents within some range of their social network and socio-economic status. Loss aversion would characterize how much risk an agent is willing to take, this could be a function of predicted weather or market variability.

3.1.4 Insights and future work

In the papers we reviewed, agricultural agents were the type most commonly represented by multiple instances within one model. Rather than using general agricultural agents, many papers represented the heterogeneity of these agents using specific attributes, such as source of water (Kock, 2008; Van Oel et al., 2010, 2012), or type of farming (Bah et al., 2006; Souza Filho et al., 2008; Farolfi et al., 2010; Espinasse, 2005). Additional attributes include socio-economic factors, farming experience, farm size (Cai and Xiong, 2017; Yuan et al., 2017), on-farm non-ag activities, membership in conservation organization (Giuliani and Castelletti, 2013), number of wells (Barthel et al., 2008), crop choice and planting date, labor force allocation, farm business structure (Holtz and Pahl-wostl, 2005), entrepreneurship and dependence on irrigation resource (Cai and Xiong, 2017). Some of these attributes can be combined and classified into specific types of farming practices that are aligned with the original AFT concept as defined by (Rounsevell et al., 2012) and (Arneth et al., 2014). Farming practices have been aggregated as profit oriented, multifunctionalist, traditional, hobbyist or part-time, and business oriented (Holtz and Pahl-Wostl, 2012; Karali et al., 2013).

3.2 Regulator

Regulators are agents that create or enforce local, state, or federal policies.This agent encompasses both policy makers who create rules and regulations and the administrators that enforce them.

Regulators allocate water and permits (e.g. pertaining to water quality), record violations, enforce associated penalties, and can develop large-scale infrastructure (Table 2, Noël and Cai (2017); Tidwell et al. (2012); Bakarji et al. (2017); Berglund (2012); Kock (2008); Berger et al. (2007)). They can affect all (or a subset of) actors within their regulatory boundaries (federal, state, council of governments, county, municipality), and actions will generally occur at the organizational/ institutional level, although decisions can be influenced by individual biases. Governance is defined broadly as means for society to make collective decisions and actions for managing common pool resources (Chaffin et al., 2016), the regulatory agent is encompassing formal governance, while informal governance might be better represented by individual agent types (e.g. home owners associations would fall under the Domestic agent).

3.2.1 Biophysical Interactions

Regulatory agents do not directly move or store water in the biophysical system, rather they influence the system via the other agents they interact with. Regulators can have access to relevant data about the system such as snow water equivalent in the snowpack or forecasted streamflow or have indirect access to this knowledge via experts with whom they communicate. They also have knowledge pertaining to past allocation rules, water rights, and water quality data (Akhbari and Grigg, 2015).

3.2.2 Social Interactions

The regulatory agent is socially connected to most other agents in the system because they are monitoring the state of the environmental system and whether other agents actions fall within the established rules and standards. They can communicate to other agents about the state of the system through direct communication, or through other means such as media outlets (Bakarji et al., 2017). They can then enforce their regulatory actions through fees and penalties. The regulatory agent receives information about opinions and needs of other agents within their jurisdiction mainly via the interest group agent.

3.2.3 Decision-making

These agents make decisions based on established regulations, public opinion, profit, and perception of environmental conditions (Table 3). These decisions are a function of the regulators attributes which might include the spatial extent of their regulatory boundaries and the objectives of the institution they represent. Types of regulation can be represented as command and control (e.g. zoning and strategic planning), or incentive-based. The rules and regulations could be parameterized based on constrained optimization problems (Bakarji et al., 2017), or actual regulations obtained from local, state, or federal agencies. Public opinion could be a component of their decision making through the influence of interest groups, and profit would capture the influence of fees/ fines and financial resources. Their perception of environmental conditions could be based on data they obtain from the system, or indirect information that they receive through other individuals (Akhbari and Grigg, 2015).

3.2.4 Insights and future work

Adaptive management literature suggests that decentralized governance is ideal for sustainable resource management, but governance is complex and some key management decisions can irrevocably alter future system configuration (e.g. systems are path dependent). They can be represented by hierarchical, multi-level networks (Kenbeek et al., 2016). Representation of actual network structure is important for evaluating adaptation, coordination and conflict resolution (Chaffin et al., 2016; Newig et al., 2010; Rathwell and Peterson, 2012) but was not represented in the reviewed literature. Tribal water rights, for example, are often legally mandated at the state or federal level, while management decisions might also be influenced by interest groups that represent them.

3.3 Domestic

Domestic agents consume water for indoor and outdoor residential uses.

The main role of domestic water users is to consume water for indoor and outdoor residential uses (Table 2). They are often modeled at the individual or household level, which enables their use in modeling population growth and expansion preferences (Zellner, 2007; Berglund, 2012; Nikolic and Simonovic, 2015). They can also implement various water saving strategies, which occur at the household level, such as installation of water saving appliances or adoption of water reuse programs (Elhay et al., 2016; Soboll et al., 2011).

3.3.1 Biophysical Interactions

Domestic water users directly remove water from the system both for consumptive and non-consumptive use. They generally receive water from the system via the water utilities, or from individual groundwater wells. Indoor water uses return water to the system via wastewater treatment plants or individual septic systems, which in turn affects the local water quality. Outdoor water uses can result in changes to evapotranspiration, shallow groundwater recharge, and water quality.

3.3.2 Social Interactions

Domestic agents receive secondary information about the system through friends, family, and neighbors, as well as news and media sources (e.g. Elhay et al. 2016; Barthel et al. 2008). This information generally pertains to the hydrologic state of the system (drought or flood stage), water reduction goals, or limits imposed by the regulatory agents or water utilities (Koutiva and Makropoulos, 2016). Adaptations taken by domestic water users can be modeled as a function of social networks where their decisions are based on neighbors adoption of conservation practices (Barthel et al., 2008). Explicitly representing individual decision-making, allows for diffusion of actions and emergent responses to the state of the system (e.g. water use reduction during drought).

3.3.3 Decision-making

Attributes of domestic water users can reflect socioeconomic factors (Akhbari and Grigg, 2015), but household and lot size (Tidwell et al., 2012) are the primary attributes used to characterize variability within this population. These can help parameterize water use patterns and adoption of water saving strategies. For example, households with large lots sizes will likely use more water for outdoor use, and social networks might influence the likelihood of an agent adopting water conservation strategies. Their decisions would be based on minimizing costs, history of previous actions, new technology, and both local and global social influences (Table 3).

3.3.4 Insights and future work

Characterizing domestic water users is often aided by publicly available information such as census data. Further examination into how social networks and perceptions of risk influence individual decision-making will certainly create more robust models of how these agents influence the hydrologic cycle.

3.4 Industrial/ Commercial

Industrial agents use water for processes such as fabricating, cooling, washing, processing, diluting or transporting a product (Dieter et al., 2018).

The role of industrial agents is to extract and discharge water, treat discharge, and trade water quality permits (Table 2, Berglund (2012); Zellner (2007)). These agents operate at the organizational scale, and decisions are often based on allocated permits (Nikolic and Simonovic, 2015; Akhbari and Grigg, 2015). They have all the relevant operating information about their facility, namely the amount of water entering and leaving their property, past allocation rules, water rights, and assimilative capacity of the system (Akhbari and Grigg, 2015).

3.4.1 Biophysical Interactions

Depending on the industrial agents source of water and location of discharge, they can directly impact instream flows and downstream water quality, or groundwater levels and quality.

3.4.2 Social Interactions

These agents communicate with downstream water users when they surpass water quality standards and with other industrial agents or regulatory agents to buy additional water quality permits. The attributes of this agent will be dominated by characteristics of the industrial process they are performing, and their associated water rights, or pollution permits (Nikolic and Simonovic, 2015; Akhbari and Grigg, 2015).

3.4.3 Decision-making

Industrial agent decisions would be based on minimizing costs, which are a function of regulatory restrictions and fees in addition to demand for their good/ service, itself a function of local and global markets (Table 3). They would also operate based on previous operating procedures, with adaptation of new technologies being a function of social pressures and profit margins. Hypothetically they could also make decisions to minimize environmental impacts, but this would largely be a function of social pressures (aggregated by the interest group agent) and regulatory mandates.

3.4.4 Insights and future work

In our review we found only 5 papers that included industrial or commercial agents. Thermoelectric-power generation in the U.S. accounts for 41% of freshwater withdraws (Dieter et al., 2018). Although consumptive use is relatively small, incorporating these facilities in modeling efforts will be critical to modeling across the food-energy-nexus (Kimmell and Veil, 2009; Tidwell et al., 2013; US Department of Energy, 2014). Given the scale of their influence on water resources, incorporating the actions of industrial activities in ABMs could provide additional insight about overall system function.

3.5 Water Utilities

Water utilities are public or privately owned organizations that obtain, treat, and deliver water to service connections.

In order to provide uninterrupted supply of safe, pressurized drinking water, utilities control large distribution systems, construct and maintain infrastructure, and identify new water resources (IDWR, 2018). These agents generally function at the organizational level. The most common way water utilities have been included in water resources ABMs is in implementing and enforcing water use restrictions (Table 2).

3.5.1 Biophysical Interactions

Water utilities directly affect stores and fluxes of water in biophysical models by withdrawing groundwater or surface water, and by treating wastewater and return it to a given river reach. They can also indirectly impact fluxes of water through water restrictions and rate structures which influence how much water domestic agents use. Water supply companies have direct access to current and future water use needs (e.g. total domestic demand now, and in the future with urban growth), which allows them to make decisions regarding the development of new infrastructure or implementing water use restrictions.

3.5.2 Social Interactions

They communicate conservation goals and water use restrictions to their users and can relay warnings or use restrictions regarding drinking water quality (Barthel et al., 2010). They might have more direct communication with regulatory agents and serve as an intermediary between them and their customer base. They can also mitigate issues by using reserves without informing the customer base (Barthel et al., 2008).

3.5.3 Decision-making

Water utilities will make their decisions based on profit margins, history, growth/development projections, regulatory mandates / operational targets, and technological advances (Table 3). Their profit margins will determine the scale and timing of infrastructure improvements and expansions. The decision to do this can be a function of growth projections (which could be information supplied by the economic agent) and expected changes in water supply (e.g. climate change projections). They will be constrained by the regulatory agent to provide some level of water quality, and quantity in their service area. Technological advances might be adapted based on demand or social pressures.

3.5.4 Insights and future work

Attributes of water utilities include information on their customer base (number of people they serve, and the timing of that service), characteristics of the water source (supply area, withdraw limits), and attributes of the organization itself such as ownership and management (Baietti et al., 2006), the affiliated water supply companies and transboundary transfers (Barthel et al., 2010). These attributes could be used to designate different functional types for water utilities. For example, public water systems are designated based on population served and duration of service, while other ownership types include municipal, investor-owned, conservancy district, cooperative, not-for-profit, and regional water districts. The variability in utilities could impact operating procedures, growth, and water pricing. This highlights the appeal of creating functional types, they can capture and synthesize much of this variation in a way that makes model building more tractable.

3.6 Interest groups

The interest group agent includes individuals or organizations that use various mechanisms to impart behavioral change in the system.

The role of interest group agents is to impart influence in the system via education and outreach to influence public opinion, or through advocating for government and industry to change regulations and policies (Table 2). They can represent environmental NGOs, tribal communities, recreational users, the agricultural sector, or taxpayers in general (e.g. (Thoyer et al., 2001)). As such, they might operate at the organizational scale, but they can influence individuals within other agent types or at the institutional/organizational level in regard to policies and regulation as dictated by the regulatory agent.

3.6.1 Biophysical Interactions

Interest groups do not directly change stores or fluxes of water, but they do monitor the biophysical environment in regard to the interests of their constituents. Influence on the biophysical system is most likely to occur through exerting influence on other functional types through social interactions.

3.6.2 Social Interactions

The influence of interest groups is imparted through a variety of social mechanisms. These agents have information on rules and regulations set by regulatory agents, other agents compliance to those rules, and satisfaction of the stakeholders they represent. They can serve as a watchdog where they help to enforce agreements monitor compliance, or prevent illegal activities, and file lawsuits, or alternatively, as an enabler where they provide resources for capacity building, facilitate network building and funding acquisition (Crosman, 2013). These groups can also can represent an expert role in the system through their work to use science to inform and guide management decisions, or as a mediator between regulatory agents and others in the system (Islami, 2017). Interest groups can also play a manager role in the system through hands-on management of restoration projects or conservation easements or reserves (e.g. land trusts management partnerships, strategic planning tools, acquisition and zoning). Finally, they can play an important role in disseminating information to other actors.

3.6.3 Decision-making

Interest groups will decide to communicate with other agents based on their social network/capital, the environmental state of the system, history of interactions, and new technology (Table 3). These agents may be programmed to monitor some measure of agent satisfaction for collections of other agents assigned as their constituents, and report the aggregate satisfaction to regulating agents. For instance, an interest group agent might keep track of how often industrial agents cannot use their allotted water right and report the total amount of unsatisfied demand to a Water Utility agent that may, in turn, develop new water resources to satisfy this unmet demand. Or they might monitor how many times an agent has violated terms of water quality permits and report them to the regulator agent. Their previous interactions will influence current decisions (e.g. continued pressure for instream flows for fish). They may monitor new technological advances and can promote those options to other agents in the system to meet their mission.

3.6.4 Insights and future work

Interest groups represent a heterogeneous set of organizations. Identifying the AFTs associated with these organizations could help classify their different objectives and the ways in which they influence a CNH system.

3.7 Reservoir Management

Reservoir management agents represent reservoir operations which control the timing and amount of reservoir outflow.

Rather than using hydropower as an independent agent (which was common in the literature review: Akhbari and Grigg 2015; Kock 2008; Giuliani and Castelletti 2013), we posit that a reservoir manager has a unique role in water management which could represent the interest and knowledge of agents from private, federal, or state-owned reservoirs (Table 2).

3.7.1 Biophysical Interactions

Reservoir managers have the largest direct role in water management by determining reservoir outflow. This sets the downstream discharge, as well as the areal extent of the reservoir which impacts total evaporation and local recharge (through groundwater-surface water interactions).

3.7.2 Social Interactions

Reservoir release schedules are optimized for specific objectives such as flood control, late season irrigation releases, or consistency in hydropower production (BPA et al., 2001). This requires coordination between federal, state, and private dam owners in order to provide these downstream services. For example, the Coordinated Columbia River system includes run-of-river dams, storage dams, hydropower generation, and multi-purpose facilities which function based on the Pacific Northwest Coordination Agreement, the Columbia River Treaty, federal flood control statutes, and various environmental regulations (BPA et al., 2001). This will result in frequent interactions with the regulatory agent who, might be providing the rules and regulations for reservoir management (e.g. Army Corps of Engineers Water Control Manuals). Although reservoir managers might be represented as an individual, they are reflecting institutional/elective procedures (see Saqalli et al. 2010)

3.7.3 Decision-making

Reservoir attributes that impact agent decision-making include the type of dam (e.g. run of river), total capacity (live/dead storage), number of turbines, energy demand and pricing (Akhbari and Grigg, 2015), and potential exposure to litigation (Kock, 2008). Cai et al. (2011) represent multipurpose reservoirs (water supply, flood control, and hydropower generation) with behavior rules based on operational targets (from regulatory agent) and maximization of hydropower generation. Their decisions will also be based on historical operations of the dam and profit margins (Table 3).

3.7.4 Insights and future work

Interestingly, decision-making regarding dam operations were not represented often in the reviewed ABM literature. For example, Van Oel et al. (2012) use an empirical data set on reservoir releases instead of implementing autonomous decision-making. Representing individual decision-making in reservoir operations is an important source of variability in these systems because operational targets only serve as a guide and are not codified law (US Army Corps of Engineers, 1985). In the

U.S., Patterson and Doyle (2018) determined the occurrence and magnitude of departures from operational targets by comparing the rule curves from water control manuals to actual reservoir outflow. This type of dataset could be particularly valuable for validating ABMs that aim to capture this variability.

3.8 Economic Institutions

Economic agents manage capital invested in the water sector to either reduce water-related risks or increase capital gains from water-related investments.

Water supply intrinsically affects, and is affected by, economics. The role of economic agents is to manage capital invested in the water sector, and provide information to other agents about the economic state of the system (Table 2). Economic agents can also create private and public water markets, sell insurance (e.g. flood), or oversee water banking (Ghosh et al., 2014), taxes, subsidies, infrastructure investments (Dadson et al., 2017), fines, transaction costs, and conservation rate structures (Michelsen et al., 1999; Mulligan et al., 2014).

3.8.1 Biophysical Interactions

Economic agents do not have any direct influence on stocks and flows of water. However, they potentially exert strong indirect influences on fluxes of water because they may preferentially provide financing and access to capital for water management technologies that are likely involve less risk. In doing so they convey exogenous signals from regional and global markets to actors within the local model. As such, they may significantly constrain the decisions of other agents, particularly the Agricultural, Municipal, Domestic, and Commercial/Industrial agents.

3.8.2 Social Interactions

Water demand is variable over time due to population and business growth, while costs are variable due to the source and availability of water. Therefore, evaluating supply and demand of water can be instrumental in assessing water management plans, options for urban growth, risk pooling/shifting

(Baum et al., 2018), and both industrial and agricultural business strategies. Economic agents can interact with any other agent, either directly (e.g. providing flood insurance, (Dubbelboer, J., Nikolic, J., Jenkins, K., Hall, 2017)) or indirectly (characterizing the economic state of the system, or household water costs Rehan et al. 2013). These decisions create dynamic interactions between economic growth and things such as infrastructure investments and associated changes in risk from hazards such as flooding (Dadson et al., 2017).

3.8.3 Decision-making

Economic agents could be parameterized based on local and/global market influences and social capital (Table 3). They would be aggregating information on these markets and transmitting this information to other agents, while the likelihood of adopting a new market strategy could also be a function of social interest as aggregated by the interest group agent. Attributes of the economic institutions will reflect the ways in which they either infuse, restrict, or amplify financial benefits of various management strategies. In Dadson et al. (2017) their conceptual model describing investment is based on the actual hydrologic state, and the perception of the hydrologic state, in addition to potential technology or policy driven reduction in water use efficiency. This would require both hydrologic predictions and a stochastic component that could be driven by an ABM. The economic agent could also act as a simple interface to a more complicated economic, or hydro-economic model, which sets the rules by which other agents make decisions based off of (e.g. market prices for crops, labor costs etc., Schlüter et al. 2009).

3.8.4 Insights and future work

There has been extensive research that aims at assessing the value of ecosystem services (e.g. Huber-Stearns et al. 2017; Mavrommati et al. 2016) in order to quantify outcomes that are omitted by conventional economic valuation. Agent based models could be a particularly valuable tool for incorporating individual values and their decisions into economic analyses which often make assumptions about the rationality of actors and availability of information (optimal control models, Mulligan et al. 2014).

4 Example of conceptual model development using agent types

Water scarcity is of particular importance in the western United States where flood control volumes in reservoirs is needed to mediate flood risk from annual snowmelt, but water storage is necessary for irrigation water demands later in the growing season. This example explores whether and how a system of interacting users with various objectives can simultaneously prevent snowmelt driven flooding, maintain a minimum stream flow for fish, and provide water for downstream water rights holders. Here, we use this common scenario to show how agent types interact with one another and with the biophysical environment (Figure 3). This conceptual outline illustrates the value of a general typology and provides other modelers with a useful starting point in formal model construction.

On annual timescales the regulator agent creates and enforces rules for the system and coordinates with the reservoir manager. The factors influencing reservoir operations will be based on the dam objectives (e.g. flood control, storage, and maintaining environmental flows) and the individual reservoir manager. Details on the individual controlling reservoir outflows could include risk tolerance, hydrologic knowledge in the form of access to data on snow water equivalent or predicted streamflows, memory, and/or social connections with other agents that are dependent on in-stream flows. In the Boise River Basin, once the flood control season is over, decisions regarding the release of water from the dam are determined by the water master (agricultural agent) who determines how much flow is needed to fulfill water rights. This is based on communication with individual farmers within the irrigation district(s), but has to fall within the regulatory statutes associated with their water rights (thereby having oversight from the regulatory agent). Farmers within the irrigation district determine how much water they need based on the number of acres they are irrigating and crop water demand, both of which would have been determined at an earlier time step as a function of agricultural markets and other economic factors (economic agent), and potentially interactions/communication with other agricultural agents. This series of decisions by the individual farmer results in withdrawals from the canal (q_c), a water flux onto their fields via irrigation (P_{eff}), increased evapotranspiration (ET) due to decreasing water limitation, and potentially shallow groundwater recharge or surface overland flow. Return flows, or surface water-groundwater exchange between the irrigated land and the canal can then be calculated (R_f).

The utility of the agent typology is that we can represent the influential agents with or without data on individuals, thus bridging theoretical and empirical approaches. By reconciling these approaches, we are able to create a theoretical landscape and populate it with agents using only the most relevant data. For example, we could collect data to parameterize reservoir agents, or we could represent them using just the reservoir rule curves with a variety of parameterizations for their biases. This simplification also enables clear identification of critical agents in the system. In this example, the water master is a critical link between the agricultural agents decisions and reservoir management. Without that social interaction, there would be no way to aptly capture reservoir discharge after the flood control season. The roles associated with each agent allows for easy identification of which hydrological variables they affect or respond to. For example, precipitation could be applied to the basin that the reservoir manager is responding to, or it could be the effective precipitation that the agricultural agents apply to their fields. This simplifies our ability to transfer the model to another basin or combine with other basins to create a regional model.

5 Discussion

A standard set of agent types affecting water resources will benefit the increasingly frequent efforts to model water resources from a CNH systems perspective. Current models often define individuals in a given system in an ad-hoc fashion, which limits the clarity and transferability of models across systems and scales. The proposed agent typology will aid in future model development by explicitly defining the roles of agents and the biophysical pools and fluxes their decisions influence. This will also aid multi-method modeling approaches or the integration of submodels which could alleviate some of the imbalances in process detail of social and biophysical components of the system. Using the same set of agents across water resources ABMs could result in transferable models that can be scaled from individual basins to entire regions with multiple interacting management districts. Consistent classification of actors will also support comparison of models and modeling results from various CNH systems.

5.1 Findings from Literature Review

Although there were commonly used agent types in our literature review, such as agricultural and domestic water users, there were a few agent types not represented by the previous classification scheme suggested by Akhbari and Grigg (2015). These agents were grouped into the new agent types that we have defined as: interest groups, economic institutions, and reservoir managers. The only agents found in the literature that we omitted from the classification scheme were representing physical pools or fluxes (Cai et al., 2011; Bithell and Brasington, 2009), or behavioral differences (Farhadi et al., 2016). We believe it is critically important that future ABMs use hydrologic models (rather than agents) to represent those pools and fluxes in order to capture potential emergent dynamics within the natural system.

Interestingly, although reservoirs represent large pools and fluxes of water, they are not commonly incorporated into current water resources ABMs. This could be due to the extensive use of system dynamics models to optimize reservoir operations (Ahmad and Simonovic, 2004, 2000; King et al., 2017)), or other operational models for reservoir system management (RiverWare Zagona et al. 2001, WRAP Wurbs 2005), but nonetheless highlights an avenue of research that has not been thoroughly explored using ABMs (but see Becu et al. 2003; Jeuland et al. 2014). Reservoir managers do have to follow predetermined guidelines and rule curves, but they are influenced by their understanding of the system, individual biases, and state of the system (Patterson and Doyle, 2018), which was not explored by the reviewed papers. Although regulatory agents are used in many of the reviewed ABMs, there were limited examples of how various governance structures, or regulatory mechanisms affected the hydrologic state of the system (but see Rathwell and Peterson 2012). Likewise, economic agents were not commonly used in the reviewed ABMs, potentially because of the popularity of hydro-economic modeling (see Harou et al. 2009 for a review) which is grounded in the optimization methods of traditional economics which does not generally include variable information availability, or non-rational decision-making. Agents that fall under interest groups were variable across the literature, but we have identified that their main mechanism of affecting water resources is through communication with their associated constituents and regulatory agents.

5.2 Limitations of the typology approach and future work

Making decisions about where to delineate the boundaries between agent types, and how to classify types that dont fit neatly into the classification scheme, are inherent challenges in creating a classification of groups of individuals. In water resources, agents often belong to more than one of our agent types. For example, water districts in Idaho represent the interests of irrigators, determine the flows of water through the canals in their district, and are governance units as designated by the state (Idaho Department of Water Resources). While this is a common issue, the solution is to determine which of those roles are most important for the particular modeling exercise, and/or explicitly state how the agent is affecting pools and fluxes through specific functions associated with a given type (e.g. they could enforce regulations via their control over the delivery of water). Future work would benefit from empirical studies characterizing individuals within each agent type, much like the AFTs created for land owners in Blanco et al. (2015). These types of empirical studies could elucidate if and how the functional roles of agents within the same type change from one location to another. Further work should strive to identify the frequency and form of information that impact decisions, further improving our understanding of what information is needed as input into ABMs. Development of standard APIs for ABMs would also be beneficial, but will require a community effort, after foundations such as these typologies have been agreed upon.

Any effort to model a CNH system requires careful consideration of how to best operationalize individual and collective decision making. One advantage of an agent-based model is its ability to flexibly incorporate heterogeneity in behavior and decision making. However, this flexibility has resulted in a lack of consistency in how decision-making is captured in different models, and inadequate grounding in established theory (Groeneveld et al., 2017). Furthermore, until recently theoretical motivation of model development too often relied exclusively on the rational actor model (Schlüter et al., 2017). One unrealized merit of the AFT approach is that functional types could be defined to capture and represent different theoretical assumptions about human behavior, thereby allowing for an examination of these different theoretical approaches. In constructing our agent typology, we chose not to commit to a particular theoretical approach, but rather to identify and explicate a number of important influences on behavior that apply to all agent types and should likely be considered in model building, including learning from previous experience, information transmission and learning from others, environmental interactions and economic factors.

One synthetic, yet relatively under-appreciated approach to conceptualizing behavior in coupled models is the cultural evolutionary perspective. The process by which certain ideas and beliefs spread at the expense of others (via learning and imitation) is through cultural evolution (Boyd and Richerson, 1985). A broad body of theoretical work in the field of cultural evolution has identified the learning strategies (e.g., imitate the most successful; imitate the majority) that are likely to evolve under environmental uncertainty, and their population-level outcomes (Mesoudi, 2011). The cultural evolutionary perspective thus specifies the social processes that are needed to explicitly model the co-evolutionary dynamics of CNH systems (e.g. adaptation under environmental uncertainty), and therefore could be useful in the field of socio-hydrology, which seeks to specifically understand these co-evolutionary processes (Sivapalan et al., 2012)). Models operationalizing behavior using a cultural evolutionary perspective have had productive impact in the contexts of sustainability (Waring et al., 2015), land-use change (Ellis et al., 2018), environmental management (Baggio and Hillis, 2018), but only recently have scholars explicitly applied cultural evolutionary ideas to a water resources management model (Yu et al., ????).

5.3 ABM documentation standards and considerations for creating a water resources ABM

Documentation of ABMs is imperative for replication and transferability of CNH models. Description of key attributes such as geographic extent and resolution of both social and biophysical components can help in communicating the nature of the questions and model itself. Our water agent types should aid in determining which agents are relevant to the research questions by enabling identification of which agents influence the largest pools and fluxes of water, and which are most important for a specific water quality/quantity problem. The scale of aggregation for agents refers to whether an agent is representing an individual, an organization or institution, and correspondingly determines the degree of heterogeneity needed to describe agent attributes within each functional type. This is an important stage for determining whether a hierarchical structure or other scale-dependent relationship exists between and among the selected agents. Assigning agent attributes then sets the degree of heterogeneity the ABM is representing, and the range of variability that can occur in their decision-making process. This heterogeneity, captured within the water resource typologies, can then be scaled up to model CNH systems at regional to continental scales. In this way, a model developed for an individual city or watershed could be expanded to include multiple cities, by simply increasing the spatial extent of the model and the number of agents. Rather than having to redefine how individuals influence water resources, it would only entail defining which stores and river reaches the new agents draw from and return water to.

One challenge with evaluating ABMs (or systems models in general) is the inherent complexity of modeling both social and ecological systems. Given the ad-hoc nature of many ABMs, various protocols and frameworks to improve transparency and replicability of ABMs have been developed by the community (Grimm et al., 2010; Müller et al., 2013; Grimm et al., 2014; Wilensky and Rand, 2015; Schmolke et al., 2010). The ODD (Overview, Design concepts, Details) protocol was created as a common structure for describing ABMs (Grimm et al., 2006) and updated by Grimm et al. (2010) to decrease ambiguities in the original ODD protocol. They stress the importance of standardized descriptions to assure models are described completely and consistently. The need for documenting additional details about human decision-making was highlighted and appended to the ODD by (Müller et al., 2013) to include more details about the empirical or theoretical reasoning behind the choice of decision-making models (ODD +D). Because the model development process is iterative Grimm et al. (2014) proposed a standard format and terminology for documenting models and improving their transparency, much like a lab or field notebook (TRACE: TRAnsparent and Comprehensive Ecological modeling documentation). Adoption of these protocols can further the culture of good modeling practice such as in the Community Surface Dynamics Modeling System (Hutton et al., 2014; Peckham et al., 2013). The utility of these protocols had already been demonstrated by the CoMSES Network OpenABM Computational Model Library which supports the reproducibility and reuse of over 500 ABMs (comses.net).

6 Conclusions

Coupling ABMs with physically based models will become an increasingly important line of inquiry in order to assess how the intersection of climate change, changes in water resource management, and social networks affect social adaptation and its influence on, and feedbacks with, the biophysical system. Describing and using a common set of water resources agent types will expedite model development, simplify integration of models, and potentially increase synthesis of findings across systems. This agent typology will simplify representations of nested, or hierarchical structures that are present in water governance which might be analogous across similar basins. This is particularly useful in regions and circumstances where data characterizing facets of agents is scarce or must be inferred indirectly. Using one set of agent types for water resources ABMs will also result in more transferable models that could be used to capture high resolution dynamics at the regional scale and could be used or expanded upon to further assess integrated food and energy systems.

Our literature review highlights a range of future work for the growing effort to model CNH systems. Empirical work on the variability of reservoir managers biases, governance structures, and information flows would help parameterize agents. Balancing the process detail of social and hydrologic flows will continue to be challenging, but requisite to capturing emergent dynamics of our water resources.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

Conception of creating water resources agents AF and KEK. KEK preformed the literature review and organized the findings; All authors contributed to the development of the agent typologies. KEK wrote the first draft of the manuscript; All authors edited the manuscript.

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Data Availability Statement

The datasets generated for this study can be found in HydroShare. Kaiser, K.E., A. Flores, V. Hillis (2018). Literature Review of Water Resources Agent-Based Models, HydroShare, [https://www.hydroshare.org/resource/4294e9cedfca49838c2b191bc6f62260/].

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Tables

Table 1: Common modeling approaches in coupled natural human systems, and associated benefits and limitations.

Approach	Benefits	Limitations
System Dynamics Models	Capture complex and nonlinear feedbacks and relationships	Simplification of system components, where some features might have greater fidelity to certain processes than others.
Hydro-economic models	Water demand is evaluated based on value, and opportunity costs can be assessed over time. Often use high fidelity hydrologic and economic models that capture important (spatially distributed) system processes.	Decision-making is often based on complete information and rational choice (e.g. net benefit maximization), social structures are not included. Heterogeneity among agents is not easily represented, and as such, actions of individual agents cannot be easily replicated (53; 47)
Socio-hydrology	Seek to capture how hydrologic and social dynamics influence each other and evolve over time (101; 100). Hydrologic processes are well captured by physically based models.	Mismatch in the timescale of environmental management versus scales of the processes being managed (99). Complex social dynamics are sometimes represented by a single parameter (32), but recent papers highlight the ability to create truly coupled models such as in (52; 71)
Agent Based Models	Can explicitly incorporate complex human dynamics motivated by social theory (117). Can represent dynamic interactions between humans and the environment.	Local specificity of models makes comparison of findings challenging.
Agent typologies	Categorizes the predominant functional roles of individuals in the system, thereby standardizing the possible input/output variables an agent can influence.	Oversimplification of the variability within the population, sub-classification of AFTs might be necessary in some contexts.
Agent Functional Types	Characterizes the heterogeneity within a given agent type, allowing for variability in decision making strategies, goals and preferences (21). Can also simplify scaling to larger extents and incorporating greater number of agents (5).	Creating these might require larger amounts of data, or expert knowledge that can sufficiently characterize the variability, while being general enough to be applied to large geographic extents (90).

Table 2: Water resources agent types, roles and associated citations. Roles identify the activities the agents perform.

Agent	Roles	Citations
Agriculture	Water demand	82; 124; 98; 4; 15; 38; 41; 42 81; 91; 103; 114; 25; 94; 105
	Water distribution	17; 15
	Groundwater banking	69
	Conservation practices	36; 98
	Discharge water	124; 38
	Negotiation	15; 38; 42
	Landuse	41; 55; 113; 122; 61; 97; 19; 69
Regulatory	Regulations	82; 106; 69; 4; 16; 61; 105
	Infrastructure	17
	Water allocation	17; 4; 34; 38; 91; 103; 114
	Incentives/penalties	106; 18; 91; 103; 25; 16; 61
	Data collection	18
	Communication	9
	Records and settles disputes	69; 16
Domestic	Water demand	106; 9; 124; 36; 4; 12; 11; 91; 16; 70
	Conservation practices	36; 12; 70
	Population growth	18; 124; 81
Industrial	Water demand	124; 81
	Water discharge	124; 4
	Water treatment	18
	Trade water quality permits	18
Water Utilities	Water distribution	12; 16; 36
	Water treatment	12
	Water use reduction goals	18; 16
	Water use restrictions	36; 18
	Water extraction	12; 81
	Infrastructure	98
	Enforcement	11; 36
	Communication	18
Interest Groups	Advocacy	61; 105
	Capacity Building	61
	Social cohesion/influence	61; 4
	Litigation	61
	Outreach	61
	Education	69
	Report Violations	4; 105
Reservoir Management	Energy production	4; 46; 63; 26; 46; 103
	Release scheduling	69
Economics	Insurance	35; 62
	Water Banking	69

Table 3: Proposed criteria that influence agent decisions, and illustrative examples of associated input/output variables. Each agent may also base their decision on other agents previous behaviors and associated payoffs, while current behaviors and payoffs may also be communicated to specified agents. These input/output variables can then lead to social learning and emergent dynamics that wouldn't be captured without incorporating social influences.

Agent	Criteria Influencing Decisions	Input	Output
Agricultural	Profit History Technology Loss Aversion Social Influence	Streamflow Market Prices Forecasted Precipitation (P), Temperature (T), Snow water equivalent (SWE)	Irrigation Return flows ET
Regulatory	Rules & Regulations History Profit Social Influence	Streamflow Water quality Canal stage	Rules & Regulations Incentives / Penalties Communication of environmental conditions
Domestic	Minimize Costs History Technology Social Influence	Air temperature Precipitation Water use restrictions	Water use (indoor/outdoor) ET
Industrial	Profit History Technology Social Influence	Inflows Regulations Market Values	Outflow Water quality Trade/buy water quality permits
Utilities	Profit History Growth Projections Technology Regulations	Water use projections Precipitation, streamflow and groundwater withdrawal forecasts	Water use restrictions
Interest Groups	Social Capital Environment History Technology	Stakeholder involvement Data from regulatory agent (water quality and streamflow)	Behavioral Recommendations
Reservoir Management	Operational Targets Profit History	Forecasts (P,T,SWE) Inflow Operational targets	Reservoir Outflow Transpiration
Economic	Local & Global Markets Social Influence	Global Demand Taxes & Tariffs Willingness to pay Willingness to sell	Commodity prices Market price of water

Figure captions

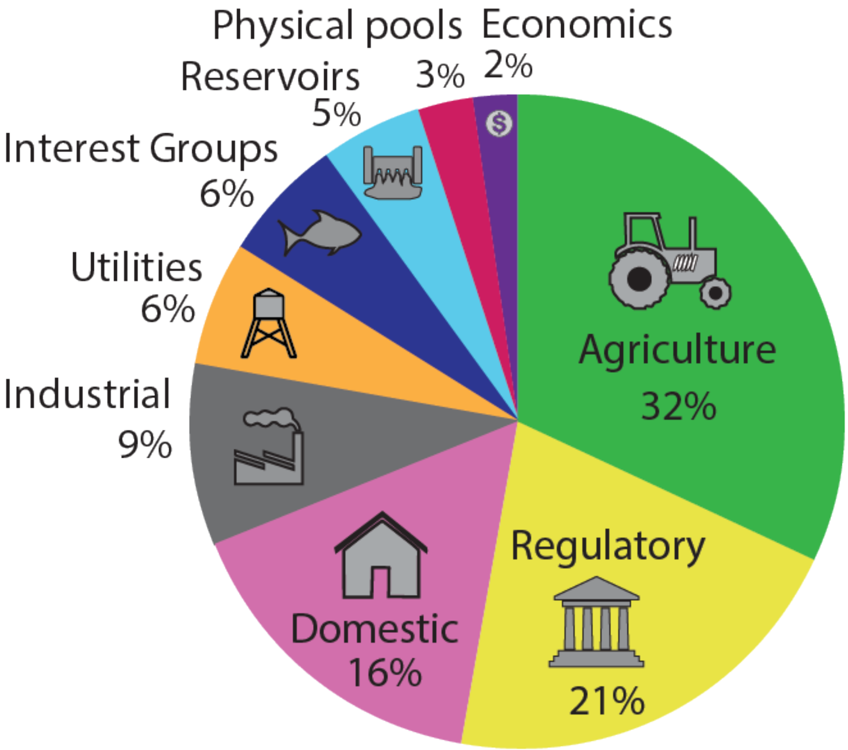

Figure 1: Percentage of each water resources agent present in the reviewed literature.

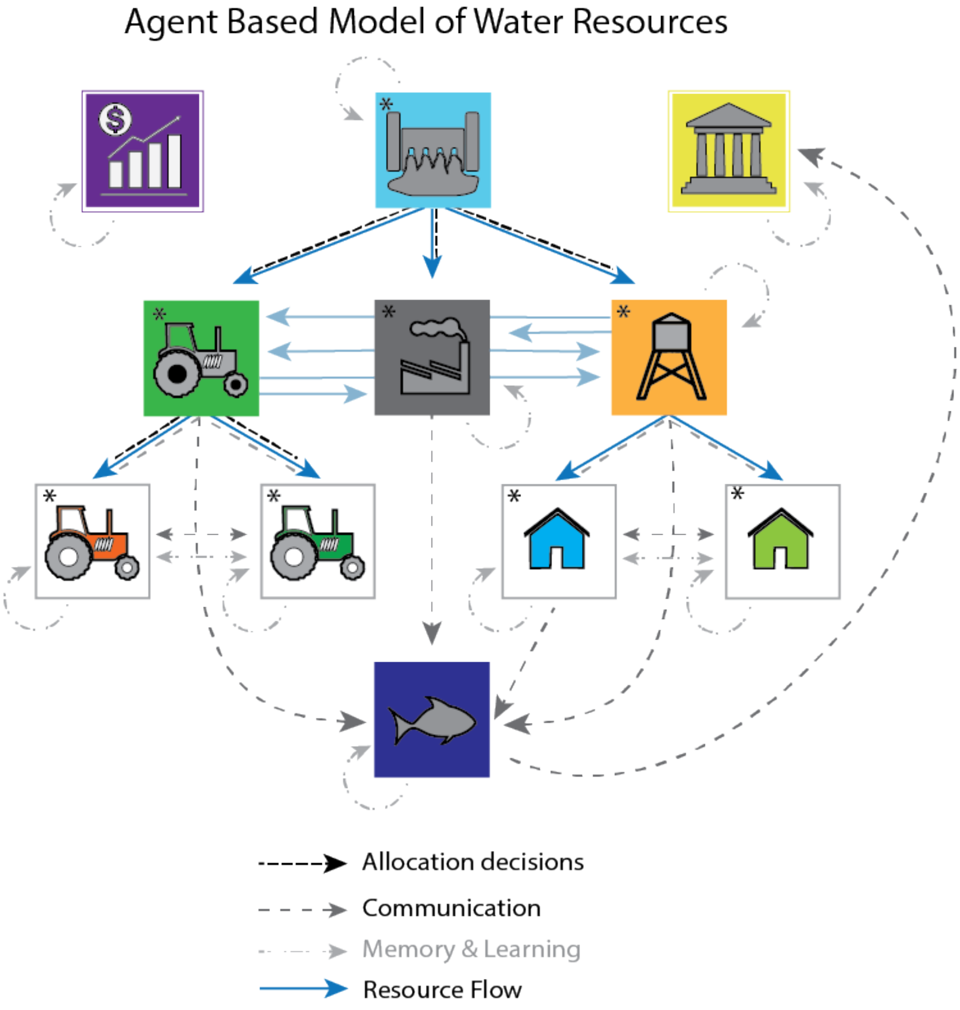

Figure 2: Conceptual inter-relationships between each agent type. Sub-models could replace an individual agent at any node or could dictate decision-making of other agents within the model. * denote agents that directly modify pools and fluxes of water, and the double box around the economic and regulator agent denotes that they have an omnipresent influence on all other agents.

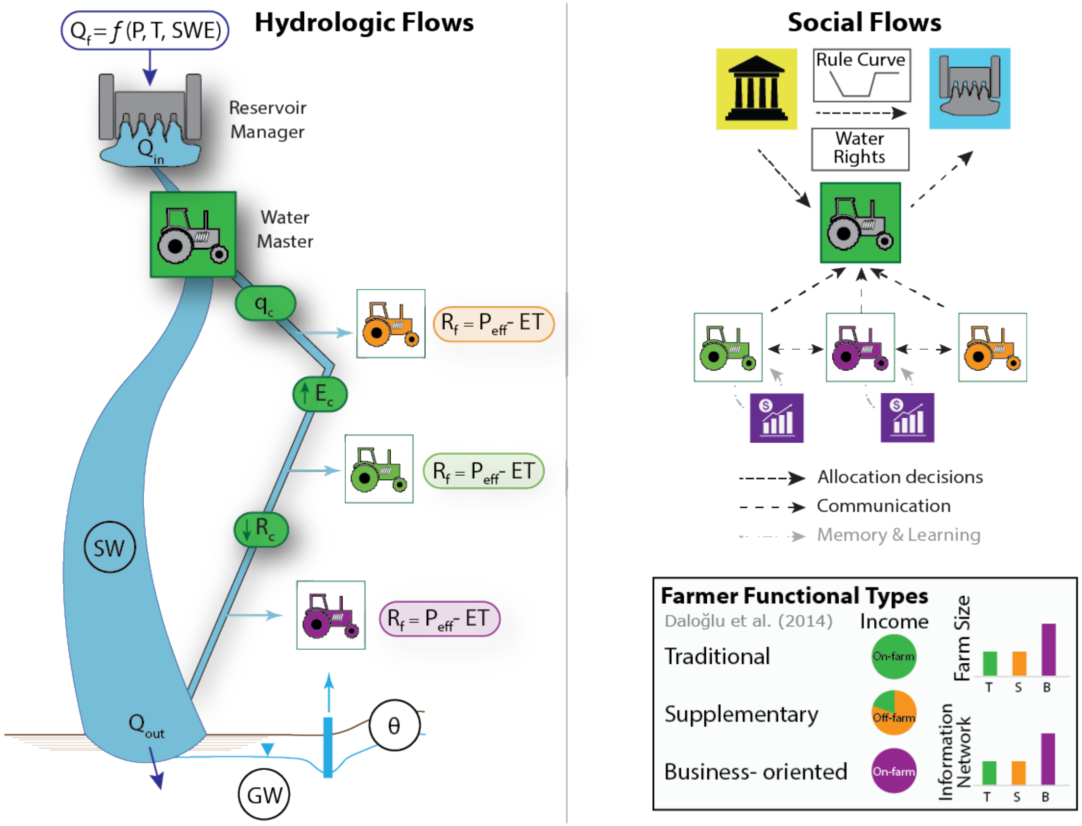

Figure 3: Illustrated example of how agents interact with hydrologic and social flows. The hydrologic flows identify which hydrologic variables each agent affects. The reservoir manager uses forecasts based on precipitation (P), temperature (T), and snow water equivalent (SWE) to make decisions about how much water to release from the reservoir into the river network (Q_{in}). The water master then withdraws water from the river to satisfy water rights for irrigators along the associated canal (Q_{canal}) which has losses to the shallow aquifer (canal recharge, R_c) and transpiration (E_c). Each farmer then withdraws water from the canal or from their groundwater well, applies it to their field (effective precipitation, P_{eff}), and makes decisions about crop cover and irrigation type which determines the amount of evapotranspiration (ET) and recharge (R_f) from their fields. The social flows show how the regulator agent influences reservoir operations as a function of rule curves (operational targets) and water rights. The water master interacts with individual farmers to determine how much water to request from the reservoir manager in the irrigation season. Each individual farmer is making decisions based on previous knowledge, and in this case, some set of economic considerations. The farmer functional types described by Dalolu et al. (30) show how the farmers decisions can be based on a combination of their information network, farm size, and income sources.