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## Identifying Emergent Agent Types and Effective Practices for Portability, Scalability, and Intercomparison in Water Resource Agent-Based Models

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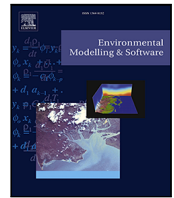
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# Identifying emergent agent types and effective practices for portability, scalability, and intercomparison in water resource agent-based models

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## ABSTRACT

Modeling coupled social and biophysical dynamics of water resources systems is increasingly important due to population growth and changes in the water cycle driven by climate change. Models that explicitly represent these coupled dynamics are challenging to design and implement, particularly given the complicated and cross-scale nature of water governance. Agent-based models (ABMs) can capture human decision-making and nested social hierarchies, however, transferability is made difficult by location-specific details. A consistent description of water resources decision-makers (individuals, groups, agencies) would advance the rate of model development and increase synthesis across systems. Reviewing water resources ABMs, we propose eight agent types and associated operational roles that modify the storage, redistribution, and water use in a system. Application of the proposed typologies and use of best practices in model documentation, will support systematic design and development of transferable, scalable, water resources ABMs and facilitate the dynamic coupling of social and biophysical process modeling.

## 1. Introduction

The capability to simulate the dynamic coupling between human activities and the water resource systems on which they depend is critically important in the context of long-term stressors such as climate change, land use intensification, population growth, and urbanization. In particular, humans impact and are impacted by the availability and quality of water resources from local to global scales. The feedbacks involved in this reciprocal relationship create a multiscale, dynamically coupled natural–human (CNH) system. Globally, water withdrawals are increasing (2500 to 4000 km<sup>3</sup> yr<sup>-1</sup> 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 et al., 2017; Ahmad and Prashar, 2010; Sehlke and Jacobson, 2005; Jeuland et al., 2014). Anthropogenic climate change and the associated intensification of the global hydrologic cycle (Huntington et al., 2018) are hypothesized to lead to increasing global average precipitation, with large variability in regional trends (Bates et al., 2008). Determining how climate change will affect this multiscale CNH system will be critical to assess potential

adaptation strategies. Agent-based models (ABMs) are particularly useful for coupling models of human systems and the hydrological systems with which they are integrated. Using ABMs to model CNH systems has become popular, in part, because of their flexibility in how they represent interactions among human actors and between humans and natural systems. In the realm of water resources, humans have modified hydrologic systems to meet demands for irrigation, industrial use, and domestic drinking water. These modifications directly impact hydrologic states and fluxes like river discharge, groundwater table elevation, and soil moisture. In addition to the complexity of natural hydrologic systems, humans have developed complicated socioeconomic, political, physical, and cyber infrastructure to coordinate decision-making and management of these water resources. Despite the flexibility of ABMs for capturing complex interactions between humans and hydrologic systems, it appears that ABMs have not been adapted for water resource system analysis with the same frequency as they have in modeling land use and land cover change (e.g. see extensive reviews, Matthews et al. (2007), D'Aquino et al. (2002), Groeneveld et al. (2017)). Potential barriers to adoption of ABMs in water resources might include (a) the highly complex and heterogeneous spatio-temporal processes associated with water resource systems across locations, (b) significant prior work using alternative classes of models that integrate human

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behavior and decision-making with biophysical models of the environment (e.g. hydroeconomic, socio-hydrology, systems dynamics), (c) the often simplistic way human influences on water systems have typically been represented in models of hydrologic systems and (d) the lack of consistency in documentation, description, implementation, availability, and transferability of code (Groeneveld et al., 2017). The development of agent functional types (AFTs) has emerged in the land use change modeling community as a vehicle to address issues of actor heterogeneity while increasing the transparency of agent representations and simplifying model development (Arneth et al., 2014). Analogous to plant functional types, AFTs characterize heterogeneity through common agent attributes (e.g. socio-demographic or economic attributes, spatial data such as irrigated acres and crop type) and common preferences associated with their objectives, which guide their decision-making (e.g. preferred management practices Blanco et al., 2015). Developing AFTs for water resource systems could help address the barriers to application of ABMs identified above, potentially leading to new insights about the emergent properties of inextricably coupled human–hydrologic systems. One challenge to identifying water resource AFTs, however, is the hierarchical and cross-scale nature of water resources management. Developing AFTs for water resource systems requires a broader framework for capturing the diversity of water management actors. A water resource agent typology would represent the operational roles of individuals or organizations and specifically identify how an agent influences water quantity or quality by altering the redistribution of water in the landscape, either directly or through interactions with other actors. Although the individuals and structure of between-actor 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.).

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 54 published studies that apply ABMs to water resource systems. From these prior studies we identify common water resources agent types across systems, define their 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 models of the biophysical system, increase the transferability and synthesis of models across systems, and potentially enable development of regional scale CNH models of water resources. This 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). In addition to developing a classification of agent types that emerges from the literature, we also investigated specific practices employed by model authors that allow for enhanced model reuse, transferability, and extensibility. We explore some potential practices that, if broadly adopted, would make ABMs of water resource systems: (1) more portable and reusable, (2) more rapidly configurable for specific locations, and (3) facilitate improved comparison and synthesis across sites and studies.

## 2. Analysis of water resources Agent-Based Models

We conducted a literature review of water resources ABM papers, allowing us to systematically identify common water resources agents. We used the Web of Science to find water resources ABMs by using the following search terms: water + manage\*/typ\*; ABM + water; Grimm et al. (2010) and Grimm et al. (2006) with water + agent. We also identified additional papers from citations of those initial papers and associated software platforms. Studies that did not have sufficient model description to characterize agents and associated roles or those that were theoretical modeling experiments (e.g. not location-

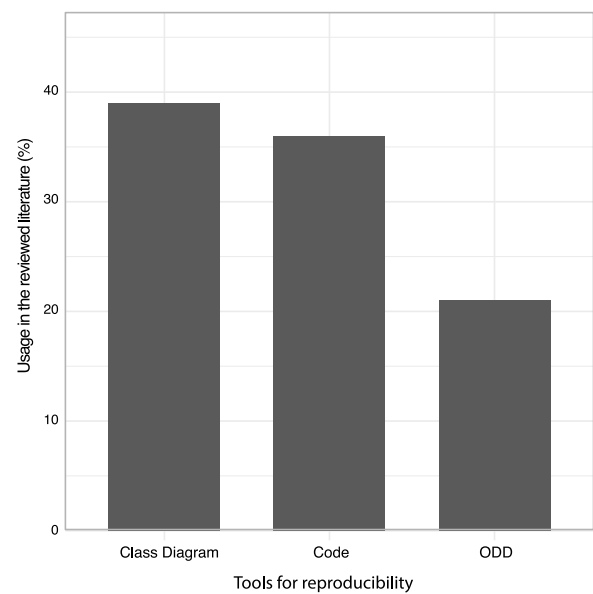


Fig. 1. Percentage of reviewed literature that used class diagrams, had open-access code, or used the ODD protocol for documentation of their ABM. Seven of the reviewed ABMs were published before ODD was developed.

or implementation-based) were excluded. The limited number of ABMs that remained after these exclusion criteria compelled us to find additional papers through the initial papers citation lists, software platforms and the follow-up papers to Grimm et al. (2010) and Grimm et al. (2006). We did not exclude ABMs from non-peer reviewed reports or theses as these ABMs were often well documented, implementation-based ABMs. The final literature to be reviewed included 54 papers, covering locations across the globe spanning Europe (16), Asia (11), North America (10), Africa (7), South America (5), the Middle East (2), and Oceania (3).

The exclusion criteria inevitably reduced the review to a small fraction of the total ABM water resources literature. The most common reason for excluding a paper was due to it being based on a hypothetical location/population. Papers were also excluded if they were variants on hydroeconomic models, that did not include explicit agents with attributes and functions, or if they described the process of developing an ABM, but not the model itself. In a few instances, a paper would present an ABM, but the documentation of the agents was so poor that we were unable to determine the specific function of agents in the model. It is plausible that this subset biases the estimate of the fraction of each agent type that exists in the literature overall, or the percent of models that use various documentation techniques. Aside from this potential bias, our reviewed literature does capture a range of ABMs based on real locations across 33 journals and reports.

### 2.1. Documenting common practices

We gathered basic information about each publication, including the journal, year of publication, and department of first author. Environmental Modeling and Software was the most common venue for publication of water ABMs, with a total of 10 papers. Another 6 journals had published between 2–4 papers and 26 other journals or non-peer-reviewed venues published a single water resources ABM. We also grouped the department or administrative home of each first author into 9 categories as a mechanism of assessing the disciplinary cross-section of authors contributing to the water ABM literature. The disciplinary nature of contributions to the literature is diverse, although Engineering and Environmental Sciences departments were the most common (43% and 22% respectively).

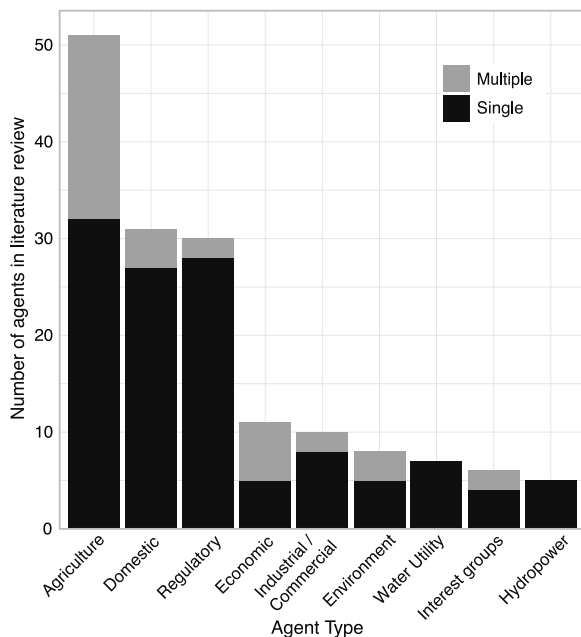


Fig. 2. Total number of each water resources agent type in the reviewed literature. Black denotes individual agents, while grey denotes agents that are represented by multiple replicates to incorporate heterogeneity of that agent type within one ABM. Note, in our classification we expanded hydropower agents to include all reservoir managers, and do not include the environment as an agent.

In reviewing each paper, we also documented the use of a number of tools and frameworks meant to make ABMs specifically, and computational models generically, more transparent, transferable, and reusable. Of particular interest was the use of class diagrams for illustrating agent characteristics and interrelationships (Fowler and Scott, 1993), making model code open source, and the use of the Overview, Design concepts, and Details (ODD) protocol (Grimm et al., 2006, 2010) for documenting ABMs. The ODD protocol was created as a common structure for describing ABMs which stresses the importance of standardized descriptions to assure models are described completely and consistently. Although 9 of the papers were published prior to the ODD protocol, the majority of papers reviewed did not use the ODD protocol, class diagrams, or make their source code open (Fig. 1). Of the 12 papers that did apply ODD, the relevant information for characterizing the model was not always presented. For example, only 3 papers that used ODD identified both spatial and temporal extent and resolution of the study area, and the total number of agents modeled. The most recent year in the analysis, 2017, was the year associated with the largest number of water ABMs published which suggests that ABMs are an increasingly common tool being used in water science.

## 2.2. Classification of water agent types

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. After reviewing the roles of each agent type we modified the (Akhbari and Grigg, 2015) classification scheme. 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 recreation agents into a broader interest group agent, to reflect that recreation agents are one type of interest group that communicates a range of desires from constituents to regulatory agents. Finally, we retained the

environmental agent for coding agents in the reviewed literature that represent environmental stores and fluxes, but do not include them in our final agent typology because they do not represent individuals that make decisions about water resources. In addition to modifying agents, we also added two new agent types that were represented in numerous ABMs, utilities (7) and economic agents (11). 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 agricultural, regulatory, and domestic users (Fig. 2). Within each agent type we documented associated roles used in each model (Table 1, Fig. 3). These operational roles encapsulate the mechanisms by which each agent type influences water quality or quantity in the system. In the following sections we define the role of each agent type, each agent's typical attributes, and potential connections with other agents (Fig. 4).

### 2.2.1. Water users

Water user agents are most commonly represented as individuals, with multiple instances of their agent type being represented within a given model.

### 2.2.2. 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 1). 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 (Fig. 2).

A wide variety of attributes are typical of agricultural agents, which were commonly represented by multiple instances within one model, where multiple types of agricultural agents were used to capture a range of attributes, in line with the AFT concept. Individual agents commonly have attributes that specify their geographic location and farm size (Cai and Xiong, 2017; Yuan et al., 2017), and socioeconomic or demographic attributes, such as income, gender, farming experience, or membership in conservation organization (Giuliani and Castelletti, 2013), while aggregate agents might represent organizations such as irrigation districts. Various attributes define the agricultural enterprise, such as on-farm non-agricultural activities, 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), 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 and Franchesquin, 2005). Agricultural agents have attributes that specify how they make decisions, potentially including heuristics for accessing, processing, and sharing information, and memory of their previous actions and those of agents within their social network. They may also have attributes explicitly defining how they are connected with other agents, via for example, communication networks.

### 2.2.3. 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 1). They are often modeled at the individual or household level, which enables their use in modeling population growth and location 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).

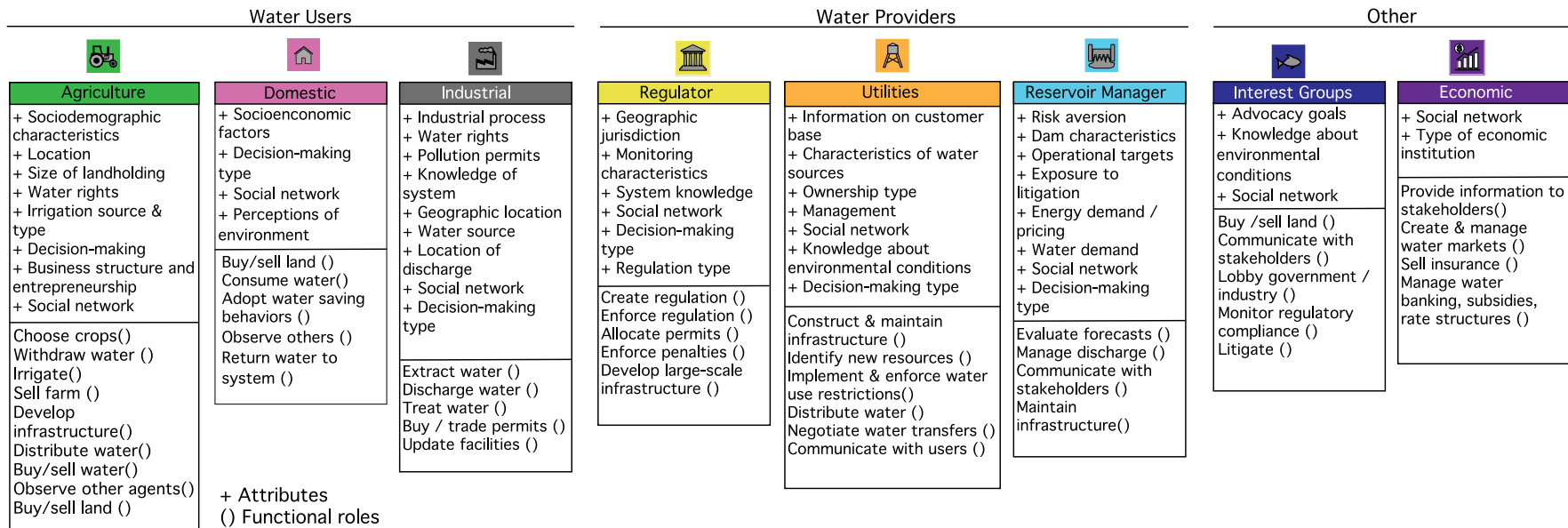


Fig. 3. Class Diagram with a non-exhaustive list of agent attributes and functions.

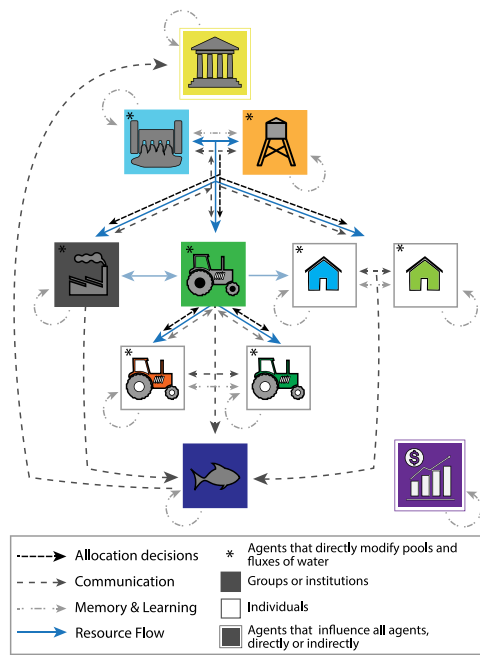


Fig. 4. Conceptual inter-relationships between each agent type. Sub-models could replace an “individual” agent at any node or could dictate decision-making of other agents within the model. Although this does not show an exhaustive set of connections and feedbacks, it illustrates the complex, often hierarchical, structure of water resources systems.

Attributes of domestic agents can reflect socioeconomic factors (Akhbari and Grigg, 2015), including household and lot size (Tidwell et al., 2012). They also can be characterized by their communication networks, which can have important impacts on their knowledge and decision-making. They can share important information about the state of the hydrological system with their networks, as well as receive information from news and media sources (e.g. Elhay et al. 2016, Barthel et al. 2008). Domestic agents’ decisions are a function of various attributes, including how they learn, memory of previous hydrologic conditions, or the criteria they use to minimize or optimize use (Table 2).

2.2.4. 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 1, 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).

The key attributes of these agents relate to the characteristics of the industrial process they are performing, and their associated water rights or pollution permits. They have important knowledge about their operations, including the quantity and quality of water entering and leaving, past allocation rules, water rights, and assimilative capacity of the system (Akhbari and Grigg, 2015). Various spatial attributes determine their interactions with the hydrological subsystem, including their geographic location, the source of their water, and the location of their discharge. They can have important communication networks, in particular in the realm of communicating with other agents about water quality standards being surpassed or to buy water quality permits. Various attributes determine how they make decisions, typically focused 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 2).

2.2.5. Water providers

Water providers make decisions about timing and magnitude of water distribution in a given system, they are commonly represented

as a single agent type, but could include multiple instances of a given agent in a large enough modeling domain (e.g. multiple municipalities).

2.2.6. Regulator

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

Regulators allocate water and permits, record violations, enforce associated penalties, and can develop large-scale infrastructure (Table 1, Noël and Cai, 2017; Tidwell et al., 2012; Bakarji et al., 2017; Berglund, 2012; Kock, 2008; Berger et al., 2007). They exist at different scales (federal, state, council of governments, county, municipality) and can potentially affect all actors within their regulatory boundaries. While their actions generally occur at the institutional level, their decisions can be influenced by the individual biases that are attributes of the individuals occupying the roles.

Regulatory agents, like agricultural agents, also operate across a particular geographic jurisdiction. An important set of attributes relates to their knowledge of the system and their ability to monitor it. They may have knowledge pertaining to water rights, past allocation rules, memory of historic hydrologic conditions, water quality data, and important environmental data such as snow water equivalent in the snowpack or forecasted streamflow. Because of their foundational presence in the system, regulatory agents have communication networks, and these networks impact their relationships with almost all other agents in the region. They also have attributes that govern how they make decisions, including heuristics based on established regulations, public opinion, profit, and perception of environmental conditions (Table 2). 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). 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.

**Table 1**  
Water resources agent types, roles and associated citations. Roles identify the activities the agents perform.

Agent	Roles	Citations
Agriculture	Water demand	Noël and Cai (2017), Zellner (2007), Shafiee and Berglund (2017), Akhbari and Grigg (2015), Becu et al. (2003), Espinasse and Franchesquin (2005), Farolfi et al. (2010) and Feuillette et al. (2003)
	Water distribution	Nikolic and Simonovic (2015), Saqalli et al. (2010), Souza Filho et al. (2008), Van Oel et al. (2010), Cai and Xiong (2017), Schlüter et al. (2009) and Thoyer et al. (2001)
	Groundwater banking	Berger et al. (2007) and Becu et al. (2003)
	Conservation practices	Kock (2008)
	Discharge water	Elhay et al. (2016) and Shafiee and Berglund (2017)
	Negotiation	Zellner (2007) and Espinasse and Franchesquin (2005)
Domestic	Landuse	Becu et al. (2003), Espinasse and Franchesquin (2005) and Feuillette et al. (2003)
	Water demand	Farolfi et al. (2010), Holtz and Pahl-Wostl (2012), Van Oel et al. (2012), Yuan et al. (2017), Islami (2017), Serrano-Tovar and Giampietro (2014), Bithell and Brasington (2009) and Kock (2008)
	Conservation practices	Tidwell et al. (2012), Bakarji et al. (2017), Zellner (2007), Elhay et al. (2016), Akhbari and Grigg (2015), Barthel et al. (2008, 2010), Saqalli et al. (2010), Bellaubi and Pahl-Wostl (2017) and Koutiva and Makropoulos (2016)
	Population growth	Elhay et al. (2016), Barthel et al. (2008) and Koutiva and Makropoulos (2016)
		Berglund (2012), Zellner (2007) and Nikolic and Simonovic (2015)
Commercial/Industrial	Water demand	Zellner (2007) and Nikolic and Simonovic (2015)
	Water discharge	Zellner (2007) and Akhbari and Grigg (2015)
	Water treatment	Berglund (2012)
	Trade water quality permits	Berglund (2012)
Regulatory	Regulations	Noël and Cai (2017), Tidwell et al. (2012), Kock (2008), Akhbari and Grigg (2015), Bellaubi and Pahl-Wostl (2017), Islami (2017) and Thoyer et al. (2001)
	Infrastructure	Berger et al. (2007)
	Water allocation	Berger et al. (2007), Akhbari and Grigg (2015), Ding et al. (2016), Espinasse and Franchesquin (2005), Saqalli et al. (2010), Souza Filho et al. (2008) and Van Oel et al. (2010)
	Incentives/penalties	Tidwell et al. (2012), Berglund (2012), Saqalli et al. (2010), Souza Filho et al. (2008), Cai and Xiong (2017), Bellaubi and Pahl-Wostl (2017) and Islami (2017)
	Data collection	Berglund (2012)
	Communication	Bakarji et al. (2017)
Water Utilities	Records and settles disputes	Kock (2008) and Bellaubi and Pahl-Wostl (2017)
	Water distribution	Barthel et al. (2008), Bellaubi and Pahl-Wostl (2017) and Elhay et al. (2016)
	Water treatment	Barthel et al. (2008)
	Water use reduction goals	Berglund (2012) and Bellaubi and Pahl-Wostl (2017)
	Water use restrictions	Elhay et al. (2016) and Berglund (2012)
	Water extraction	Barthel et al. (2008) and Nikolic and Simonovic (2015)
	Infrastructure	Shafiee and Berglund (2017)
	Enforcement	Barthel et al. (2010) and Elhay et al. (2016)
Communication	Berglund (2012)	
Reservoir Management	Energy production	Akhbari and Grigg (2015), Giuliani and Castelletti (2013), Jeuland et al. (2014), Cai et al. (2011), Giuliani and Castelletti (2013) and Souza Filho et al. (2008)
	Release scheduling	Kock (2008)
Interest Groups	Advocacy	Islami (2017) and Thoyer et al. (2001)
	Capacity Building	Islami (2017)
	Social cohesion/influence	Islami (2017) and Akhbari and Grigg (2015)
	Litigation	Islami (2017)
	Outreach	Islami (2017)
	Education	Kock (2008)
Economics	Report Violations	Akhbari and Grigg (2015) and Thoyer et al. (2001)
	Insurance	Dubbelboer et al. (2017) and Jenkins et al. (2017)
	Water Banking	Kock (2008)

### 2.2.7. 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, identify new water resources, and set water prices (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 1).

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), attributes of the organization itself such as ownership and management (Baietti et al., 2006), and affiliated water supply companies and transboundary transfers (Barthel et al., 2010). Water utility agents also have important knowledge of the hydrological system, including current and projected future water needs. This knowledge informs their decision-making about the development of new infrastructure and implementation of

water use restrictions. Their decision-making is typically based on profit maximization, projection of future development, regulations, operational targets and technological advances (Table 2). They also have communication networks that shape how they transmit information about conservation goals and water use restrictions to users, as well as to relay warnings or use restrictions (Barthel et al., 2010). They can also serve as communication intermediaries between regulatory agents and users.

### 2.2.8. 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 1).

**Table 2**  
Proposed criteria that influence agent decisions, and illustrative examples of associated input/output variables.

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

The fundamental attributes of a reservoir agent include both the characteristics of the reservoir and characteristics of the manager themselves. Reservoir attributes 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), while attributes of the manager might include things such as risk aversion, and memory of historic hydrologic conditions and associated management. These attributes impact decision-making which are often represented as operational targets (from the regulatory agent) and maximization of hydropower generation. Their decisions will also be based on historical operations of the dam and profit margins (Table 2). Reservoir managers have specific objectives that they may be optimizing for, such as flood control, late season irrigation releases, or consistency in hydropower production (BPA et al., 2001). This requires coordination among government agencies (regulatory agents), private dam owners, water utilities, economic agents, agricultural agents or interest groups and the reservoir manager.

### 2.2.9. Other water actors

These other water actors are examples of groups that may have significant influence over the use and management of water in a given system. They can increase communication between agents, or provide financial support.

### 2.2.10. 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 1). 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. They can serve as a watchdog by monitoring compliance with regulation, as an enabler by providing resources (Crosman, 2013), serve as experts by using science to inform decisions or via mediation (Islami, 2017), act as managers in specific projects, or disseminate information.

Specific attributes of an interest group agent will depend on the role that the interest group plays in the system. Interest groups make decisions based on the state of the environment and the satisfaction levels of other agents. As such, they monitor both the state of the environmental system but also the state of the social one. They can share information with their stakeholders, and can also report information about other users to regulatory agents.

### 2.2.11. 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.

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 1). 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).

The most important attributes of economic agents relate to their ability to manage capital and interact with other agents in ways that



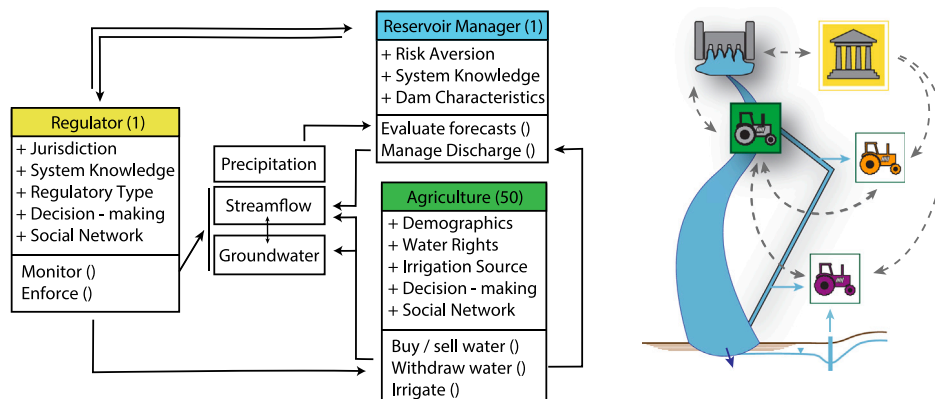


Fig. 5. Unified modeling language diagram (left), and illustrative example of feedbacks (right). Numbers next to agent names indicate the number of representations of that agent type in the example.

impact water flows. As such, their international network is one of their most important attributes. This network can be diverse and far-reaching, including both direct (e.g. providing flood insurance, [Dubbelboer et al., 2017](#)) and indirect (characterizing the economic state of the system, or household water costs [Rehan et al. 2013](#)).

#### 2.2.12. Relationships and feedbacks

A critical aspect of complex systems is the existence of feedbacks among actors and the environment, which can create emergent properties, or characteristics of the system that are difficult to predict from a consideration of the parts in isolation. Feedbacks occur when an initial change to one part of the system has an impact elsewhere, and that impact creates a new consequence for the agent that imposed that initial perturbation. An agent typology potentially aids in understanding feedback mechanisms and the components of the coupled human–environmental system through which they connect. We provide one example that illustrates how agent typologies might be used to identify potential feedbacks for more targeted study. In this example ([Fig. 5](#)) reservoir managers make decisions that impact streamflow through release of water, which reduces storage of surface water for irrigation later in the season. The decisions made by the reservoir agent balance the competing demands for minimum streamflow set by the regulator and for water storage deeded, through water rights, to agricultural agents. Agricultural agents make irrigation decisions that influence decisions made by reservoir manager, and both streamflow and groundwater levels. The regulator monitors environmental conditions and water users and may have to enforce regulations. Through this feedback mechanism the agricultural agents in this system are influencing the behaviors and decisions of the reservoir manager and the regulator through their individual and collective action, as communicated by streamflows and groundwater levels.

### 3. Discussion: Insights from review of agent types

The agent typology that emerges from our review of the literature is a framework that can support more rapid development of water ABMs, greater ability to compare water ABM studies, and enhanced capability to integrate ABMs and hydrologic models. While there are clear commonalities with previously developed agent typologies, we found additional agent types in the literature that may play significant roles in the management of water resources. Below we elaborate on why those agent types may be significant to include in a typology and articulate how some community tools and resources may serve to combat these limitations.

#### 3.1. Commonalities and distinctions from previous typologies

Although our literature review found a number of agent types in common with the classification scheme previously developed by [Akhbari and Grigg \(2015\)](#), such as agricultural and domestic water users, it also revealed additional agent types that may play important roles within specific water resources systems, and in synthesizing modeling results across systems. In particular, the additional agent types that emerged from our literature review were classified as reservoir managers, interest groups, and economic institutions.

Although regulatory agents are represented in almost a quarter 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](#)). Governance is more complex than one set of static rules, and key management decisions can irrevocably alter future system configuration (e.g. systems are path dependent). Representation of actual network structure could be important for evaluating adaptation, coordination and conflict resolution ([Chaffin et al., 2016](#); [Newig et al., 2010](#); [Rathwell and Peterson, 2012](#)) but was not present in the reviewed literature even though more realistic governance structures can be represented by hierarchical, multi-level networks ([Kenbeek et al., 2016](#)). Representing various policy scenarios may be sufficient for some modeling purposes, but further examination into how social networks and policy cycles impact the regulatory aspect of water management would certainly create more robust models of how these agents influence the hydrologic cycle ([Ellison, 1998](#); [Koontz and Newig, 2014](#)).

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](#)). Reservoirs represent large pools and fluxes of water, and thermoelectric-power generation in the U.S. accounts for 41% of freshwater withdraws ([Dieter et al., 2018](#)), yet reservoir managers and economic agents are not commonly incorporated into current water resources ABMs. This is likely due to the tendency to model these influences using hydro-economic models (see [Harou et al. 2009](#) for a review), or 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](#)) which are grounded in optimization methods that do not generally include variable information availability, or non-rational decision-making. 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](#)), factors unexplored by the reviewed papers. For example, [Van Oel et al. \(2012\)](#) use an empirical data set on reservoir releases instead of implementing autonomous decision-making. 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.

Interest groups and water utilities represent a heterogeneous set of organizations, and representing them using functional types would help more clearly define how their different objectives integrate with other actors in a water resources system. The original AFT concept as defined by Rounsevell et al. (2012) and Arneeth et al. (2014) uses attributes to classify and combine types of individuals and their respective influence on the system. Agricultural agents were the agent type most commonly represented by multiple instances within one model (e.g. farming practices have been aggregated as profit oriented, multi-functional, traditional, hobbyist or part-time, and business oriented (Holtz and Pahl-Wostl, 2012; Karali et al., 2013). Similarly, we identified that the main mechanism that interest groups affect water resources is through communication with their associated constituents and regulatory agents (e.g. advocacy coalition framework, Ellison, 1998). They could therefore be classified using functional types that represent their economic orientation (e.g., economic/non-economic, profit/nonprofit), or that represent their domain of interest (e.g. business, labor, agriculture or environment), or other aspects of their operation such as size of membership, or amount of funding, all of which would make the scale and mechanism of their impact clearer. Water utilities also have a diverse set of attributes which could be used to designate functional types. 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. These examples highlight the utility of creating functional types for each agent type, as they can capture and synthesize agent variability in a way that makes model building more tractable.

As described briefly in the methods, we explicitly omitted agent types representing stores and fluxes of water (Cai et al., 2011; Bithell and Brasington, 2009). Our rationale for this omission is that these are not agents in the canonical sense, but instead correspond to the encoding of one or more physical processes that govern the redistribution of water in the hydrologic system as an agent. This may be convenient within particular ABM software and for some research questions because it presents a relatively straightforward way to capture some nonlinear attributes of hydrologic systems. However, it potentially masks the complexities of the natural systems to which human systems are coupled and may impede model transferability by obscuring the pathways through which a more sophisticated hydrologic process model might be substitute for a natural system agent.

### 3.2. Typologies can clarify agent roles while maintaining flexibility in agent behavior

Modeling CNH systems requires careful consideration of how to best operationalize individual and collective decision-making. One unrealized merit of agent typologies is that they help partition the role of an agent in the water resources system from the various theoretical assumptions about human behavior used to model how they enact their role, thereby allowing for analyses of these different theoretical approaches specifically. An advantage of ABMs is their 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). In constructing our agent typology, we chose not to specify particular theoretical approaches, but rather to identify 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. Cultural evolution is the process by which certain ideas and beliefs spread at the expense of others (via learning and imitation) (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). This 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.).

### 3.3. Limitations of the typology approach and paths forward

In water resources, entities and/or individuals may have more than one functional role in the system, which means they would belong to more than one of our agent types. For example, water districts in Idaho represent interests of irrigators to state and federal management agencies (i.e., interest group agent), determine the flows of water through the canals in their district (i.e., agricultural agent), and are governance units as designated by the state (Idaho Department of Water Resources) (i.e., regulatory agent). Simplifying this type of real-world complexity while capturing the essential components of the process of interest is a common difficulty in the realm of CNH modeling. It is necessary, therefore to determine which of the potential roles is most important for the particular question being developed, and/or explicitly state how the agent is affecting pools and fluxes through the specific roles associated with their agent type (e.g. they could enforce regulations via their control over the delivery of water). The illustrates the reality that any typological classification will suffer from overlapping boundaries between classes and imperfect discrimination of the population into distinct groups. 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 whether 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, which would improve our understanding of what information is needed as input into ABMs.

Several practices employed by some of the reviewed papers could serve to address key weaknesses of a typological approach for agent specification. Basic documentation, for example, of ABMs is imperative for reproducibility and transferability of CNH models (Schulze, 2017). Description of key attributes such as geographic extent and resolution of both social and biophysical components provide first order information about the nature of the science questions and model itself. This basic information was rarely included in the reviewed manuscripts, and often challenging to find when it was included. The agent aggregation scale captures the degree to which an agent represents an individual, an organization, or a collection of like organizations. Documenting this aggregation scale can assist in understanding whether the simulated agent behavior parameterizes, for instance, just the preferences of an individual actor or (potentially) a complex set of policy decisions made by a large, bureaucratic entity.

Adoption of documentation protocols specifically tailored to ABMs would further assist in documenting agent roles and behaviors and presumably aid in model reproducibility and transferability. One challenge with evaluating ABMs (or system models in general) is the inherent complexity of modeling both social and environmental systems. 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 could 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). In addition to ABM specific protocols, unified modeling language class diagrams are a tool that can help modelers more clearly document the agents being simulated and their specific roles in the system. Class diagrams require model developers to explicitly and visually document what attributes agents possess, how those agents interact with other agents, and the specific functions they can perform (Fowler and Scott, 1993). The types of agents used in each model were most clearly diagnosed in the papers that used class diagrams (e.g. Barnaud et al., 2008; Becu et al., 2003). The ABM community has continued to highlight the need and desire to document, share, and increase reusability of model components, yet a panacea remains elusive, and will likely require continued community development and dialog toward adoption of standardized terminologies in deploying water resources ABMs (Bell et al., 2015; Janssen, 2017; Schulze et al., 2017).

Although imperfect, we contend that water agent typologies, when coupled with key practices for documenting agent and model descriptions, should aid in determining which agents are the most essential to represent for a particular water quality/quantity problem. More systematic efforts to document water ABMs can, for instance, aid in understanding how and why specification of agent behavior differs between two studies that involve the same agent type. It can also provide guidance for model developers as where their treatment of specific agent types departs from similar studies, either because of location, science question, or scale.

### Data availability

The dataset 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.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### CRedit authorship contribution statement

**Kendra E. Kaiser:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Alejandro N. Flores:** Conceptualization, Funding acquisition, Investigation, writing - original draft, writing - review & editing. **Vicken Hillis:** Data curation, Investigation, writing - original draft, writing - review & editing.

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