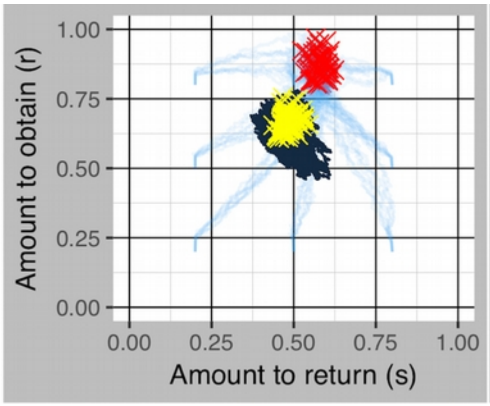
Visual Abstract



Simulation Modeling of Non-Market water exchanges: Exchange strategies reach different stable arrangements depending on the population of partners.

Understanding Institutions for Water Allocation and Exchange: Insights from Dynamic Agent-Based Modeling

Abstract

Water allocation occurs within systems that include market-driven and non-market approaches; these are often nested within complex collections of laws, contracts, and customs, and embody cultural definitions of the nature of water as a commodity or a right and the nature of fair exchanges. Understanding the dynamics of such an allocation system, including the ways that it may change through time and the ways that it can be modified to better achieve societal goals, can be challenging. One promising approach is agent-based modeling (ABM), and specifically models in which the agents dynamically adapt to the system that they create. The potential for such modeling in the domain of water systems is only beginning to be explored. We present a highly abstract but illustrative example of an adaptive system and its analysis to show the potential for the ABM approach.

Introduction

The allocation and distribution of water is one of the most significant challenges faced by human societies and must be solved at all scales from interpersonal to global. The problem of how to store and move water can be directly addressed with dams and canals, but the social questions- who gets the water, when, and how much- are, arguably, far more challenging. Water's unique position within human society and within the economy place its management in a distinctive position: water is not treated strictly as a commodity, and hence not addressed through pure market solutions, but instead is more often managed through a collection of laws, contracts, and customs. Whereas market dynamics are well-studied and understood, the ad hoc and widely varying ways that water is exchanged outside of pure markets can lead to unexpected and difficult-to-predict outcomes. When regulators, institutions, or individuals attempt to implement water management policies, often within or alongside pre-existing, historically particular arrangements, the outcomes can be difficult to anticipate. The result is that the establishment of a water exchange system can be fraught with unexpected pitfalls, even when all of that system's stakeholders have participated in the process of developing the new system's rules.

The core issue often is a notion of equity or fairness. Price fairness has been studied in economics (e.g. (Ferguson, Ellen, & Bearden, 2014)); much of the discussion there is based on buyers' perceptions of procedural fairness (that the price was determine through the application of appropriate rules) vs. distributive fairness (that the price they would pay is appropriate with respect to the price paid by others or in other circumstances). Our use of the term is analogous, but broader: we envision a scenario in which actors design and/or participate in a water exchange arrangement (whether price is involved or not), and do so while making judgments about both the procedures and their effects. For our purposes, we additionally note that the idea of fairness is constructed out of a wide range of cultural components, including the roles of the participants and the perceived and socially constructed status of the entities being exchanged (Wutich et al, 2013). Our interest lies in how the complexity of such a system may create a condition in which a system that is perceived as fair has unintended and unforeseen biases, and the dynamic outcome is far from the optimum that was intended and sought. A system that is perceived as unfair is likely to lead to conflict among the participants, and extensive negotiations or even litigation to modify the system.

This article reviews the issues that underlie challenges inherent in creating a water exchange system and examines agent-based modeling (ABM) as a potential tool for dealing with these challenges. The form of ABM examined is specifically one in which the agents are dynamic: they adapt to the system in which they participate, being shaped by it even as they shape it. We present an example in which a hypothetical system that appears prima facie to be fair is shown via ABM to contain hidden biases that might not have been expected by a designer. We show that by modeling the system these biases can be revealed, and we propose that ABM of this kind will offer a way forward for designing and understanding water allocation and management systems.

To this end we pursue three goals:

1) Review the reasons that understanding water allocation systems is especially challenging
2) Discuss ABM with dynamic and adaptive agents as a means for understanding the true dynamics of a water allocation system
3) Present an example in which an agent-based model illustrates an unexpected outcome of a presumably fair system

Market and Non-Market systems

Water occupies a unique position in the economy, one that is sometimes explicitly recognized: the European parliament, for example, has formally declared that “Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such.” (The European Parliament and the Council of the European Union, 2000) There are a number of obvious characteristics of water that push it into this special status- its availability can be unpredictable, its uses are numerous but sometimes contradictory- but the most significant attribute may be the most apparent: water is required for life, both directly (for consumption and sanitation) and indirectly (e.g. agriculture and electricity production). Hence the question of its allocation is one of the most significant questions that a society can attempt to resolve.

The attempted solutions vary widely. Sridharan et al. (2015) offer four categories by which to classify water allocation systems: market-based, command-based, culturally determined, and non-market based. Market-based systems facilitate exchanges between buyers and sellers and include a pricing mechanism; non-market systems are those in which the good or service is received without payment of any kind in return (i.e., charity). Command-based systems include a regulatory agency that requires that exchanges take place in a way that is driven by a motive other than a pure profit motive (as in a market system). Culturally determined systems are systems in which exchange is mediated by cultural norms, e.g., gift-giving relationships, kinship relationships, historical precedence or other arrangement. The authors note, however, that ‘pure’ examples of any of these systems are rare with respect to water: most systems include aspects of more than one or even all four kinds.

This variety of systems carries with it multiple ways of conceiving of water's status within the system, and, as Appadurai (2011) notes, this status can change as well; 'commodities' have value only insomuch as they can be exchanged, while other items move in different exchange spheres or have non-commodity values, such as 'priceless' heirlooms. The 'commodification' of entities is a social construction. The definition cited above of water as a 'heritage' can be read as an attempt to keep water out of the category of a pure commodity, and it speaks to a heavy symbolic consideration of water as holding more than merely practical worth. Alongside this, in the case of water, there is the fact that it is essential: denying water is denying life, leading to calls for access to water to be considered a human right (Bakker, 2007; Gleick, 1998). This complex 'biography' (Kopytov, 2011) of water as it moves among categories plays out on all scales. At the interpersonal level, Wutich (2011) observed individuals in water-scarce conditions would not deny water to their neighbors in times of shortage; at the global level, the United Nations declared in 2010 that access to water is essential to human life and dignity (United Nations General Assembly, 2010).

This ambiguous status is reflected in the variety of institutions that are established to manage and allocate water. Privatization of water is a hotly contested issue, even leading to 'water wars' (Wutich, 2009). Water pricing is rarely driven by supply and demand or even by the recovery of cost to provide it; it can be under-priced, protecting access even for the poor; or over-priced, reducing demand and promoting conservation; or priced in creative ways based on volume purchased, to achieve both of these (or other) goals (Howe, 2005). The collection of institutions responsible for managing water can exist at multiple levels (e.g. federal, state, and local) with crosscutting and overlapping boundaries and purviews (e.g. water supply vs. quality) (Murphy et al., 2014). The mechanisms for establishing rights of ownership to water, and for transferring those rights, can vary widely from place to place (Howe, 2005), as can the legal architecture by which disputes about water are resolved.

Pure (or nearly-pure) free market approaches are efficient at allocating resources, and can be applied even in circumstances where the resources are, like water, essential to life; a dramatic example is a 'market' established among food pantries (Prendergast, 2016, 2017). Despite this, water markets are the exception and not the norm, and despite the optimism for 'free market' approaches to water, water markets that have been established are in fact enmeshed in specific political, legal, and cultural milieus and have often had only limited success (Garrick & Svensson, 2018).

Non-market approaches, such as Sridharan et al.'s 'command-based' or 'culturally determined', are cases in which something other than a profit motive shapes the way that water is exchanged. How can such a system be understood, assessed, or designed? One common body of theory for the analysis of such systems this is common-pool-resource (CPR) theory, in which the resource is assumed to be capable of use for a common good but also of exploitation for individual gain. Elinor Ostrom outlined the attributes of successful institutional management of such resources (Ostrom, 2015) and provided a structure for analyzing such institutions (Ostrom, 2005).

These systems are not static. Sridharan et al. draw on Layton (Layton, 2015) to note that water exchange systems can be dynamic, adapting and changing through time. Layton's analysis proposes a theoretical framework ('Mechanisms, Actions, Structure' Theory) linked with Darwinian evolution, which permits the examination of the change in market systems through time. The shifting ways that water is managed are drawn by, and in turn shape, conceptions of equity: the negotiations among peer actors and upward and downward the various institutional and interpersonal hierarchies hinge on the conception that the allocation be fair, and the conception of fairness is itself an outcome of these historical conditions and processes that it exists within (Wutich et al., 2013). Just as the market or non-market system may evolve, so too may these underlying conceptions. Hence the overall system for water distribution must be considered as a dynamic, rather than a static, system, in which not only the structure but also the natures of the participants may change through time.

Addressing Water Allocation Systems

If the complexity of water allocation derives from layers of historically contingent institutions and equally historically particular sets of values, how can water allocation be planned for, and how can such systems be designed? The processes by which water allocation systems are created typically includes a mix of engineering (developing the physical infrastructure) and political and economic discussions. For this paper we assume that the issue is primarily a social one, albeit one that operates within physical constraints. Our question, then, is how is the issue of allocation resolved? The multiple frameworks discussed in the preceding section echo the historical answers to this question: water allocation strategies are resolved through a mix of economic competition, negotiation, bureaucratic and institutional decision-making, and political action, as well as individual participation and actions by voters and consumers.

Crosscutting these socially constructed strategies are the multiple interests of those involved in water allocation decisions. In many cases, the participants are balancing multiple, often conflicting, goals- for example, conservation and growth, or short-term economic benefits vs. long-term economic and environmental sustainability. One method that has been employed to deal with this complexity is Multi-Objective Optimization (Cohon & Marks, 1975; Reed et al., 2013). In its technical aspect, this mathematical approach can be computationally expensive, and for many complex problems has only recently become technically feasible. In a complex social context, the definition of the multiple objectives can involve engaging stakeholders in discussions about their preferred objectives and their relative weightings of those objectives. If all objectives can be met simultaneously, then there is no conflict and no challenge to the decision making, but this is a nearly impossible outcome. More commonly, achieving one objective means sacrificing others. Multi-objective optimization allows calculating the balances that are possible among crosscutting constraints and objectives that are zero-sum or in opposition. The result is a design that can be returned iteratively to discussions with the stakeholders, allowing them to find the political, economic, and cultural balance that is acceptable to them.

A complementary approach is Agent-Based Modeling (ABM) (Epstein, 1999, 2006; Epstein & Axtell, 1996). Agent-Based Modeling has been applied in a wide range of contexts, but has had its most profound impacts in the social sciences (Lansing, 2003). ABM permits the construction of a simulated system in which actors are represented individually; the actors are permitted to perceive information about their environments (including other actors and themselves) and to take actions in response to this information, typically to pursue and achieve specified goals. The actors’ internal characteristics, their ability to perceive information, and their goals and the rules they follow to take actions, can all be represented individually and in rich detail. In some cases this rich detail is unnecessary, and some of the most fruitful ways that ABM can be applied assume agents that are merely copies of each other, but whose interactions nevertheless drive the system they form in interesting directions and lead to emergent properties. However, the ability to apply ABM to cases where the actors have varying portfolios of resources and are pursuing different goals allows ABM to be used to investigate richer and more historically particular cases. Additionally, ABM allows capturing characteristics that actors in the real-world exhibit, including the transmission of information among actors and attitudes to entities in the actors' worlds and toward each other.

An important aspect of ABM is that the agents need not be static: they can not only differ from agent to agent, but a single agent can change through time, and by doing so adapt to different conditions as the simulation progresses. This capacity permits a different and more flexible way of understanding how a given system may change through time (forming a 'Complex Adaptive System' (Miller & Page, 2009)), as not only the structure of the system but also the characteristics of the actors within that system are shaped as the system's internal dynamics and logic progress.

ABM has been used to understand water management systems in a number of ways. Household water consumption has been studied using ABM in multiple contexts (Athanasiadis, 2005; Ozik et al., 2014). Bohensky applied it to the interactions among watershed managers in South Africa (Bohensky, 2006, 2013). An especially notable example of the use of ABM is WaterSim (Decision Center for a Desert City, 2017; White, 2013; Withycombe Keeler et al., 2015), an application designed for use in the Phoenix Metropolitan Area and allowing a number of communities there to explore alternative management scenarios for multiple decades into the future. ABM is especially useful in the simulation of water management because of the nature of data available (e.g. data on the outcomes of decisions at individual, local, and larger scales, but sometimes with limited visibility within these categories) However, although some examples with dynamic agents that use water do exist (Kock, 2008; Ozik et al., 2014), the application of dynamic and adaptive agents interacting in water systems is rare. This is true despite the recognition that water management systems are never static, but exist in changing contexts (e.g. population growth, changes in housing and household technology, or changes in norms around water use), for which dynamic agents would be especially appropriate research tools. In the remainder of this article we present a recent example that illustrates the potential of ABM simulations to inform the design of a water allocation system.

A Non-Market Exchange System: A Case Study

<u>Water distribution in Central Arizona</u>

We base our example on the case of Phoenix, Arizona. Phoenix draws a significant portion of its water from the Colorado River as part of the allocation Arizona received from the Colorado Compact in 1922 (U.S. Bureau of Reclamation, 1922) and the subsequent Boulder Canyon Project Act (U.S. Bureau of Reclamation, 1928). Arizona was until recently unable to use all of the 2.8 MAF (3.45 km^3) that it was due under the Compact; only with the construction of the Central Arizona Project (CAP) Canal, which draws water from Lake Havasu and delivers it to the major cities of Phoenix and Tucson, was Arizona able to use much of its allocation. The physical infrastructure that allows this is enmeshed in a social and institutional infrastructure that shapes how water is delivered to the populations in these areas. This social infrastructure has multiple layers. The operation of Hoover Dam is conducted by the U.S. Bureau of Reclamation (USBR). USBR is responsible for determining the timing of water releases upstream along the Colorado River, and these must be coordinated among the users of the river's water. The operation of the CAP Canal is undertaken by the Central Arizona Project, which manages the canal to serve the recipients of the canal's water. Rights to water are allocated from the CAP via contracts to subcontractors. Water is considered to exist in multiple categories; categories have different priorities, in accord with the system of prior appropriation employed throughout the U.S. West. The priority system means that users with 'junior' rights will, in times of shortage, lose all of their water before users with 'senior' rights will lose any.

Phoenix itself is a city of over 1 million people, but it is surrounded by a collection of other cities ranging from very large cities with hundreds of thousands of people to very small ones (populations less than 10,000). To provide water to their citizens, each of these cities has a portfolio of water rights. For some this includes rights to groundwater; for others it includes rights to water from the Salt River, which before being dammed upstream flowed through Phoenix perennially with seasonal high flows and even serious floods. For most, the water portfolio includes mixes of these, rights to large or small amounts of water that holds a specific priority depending on its physical source and the rights that were originally awarded and transferred when the rights were acquired by the municipality.

Manager Decisions

Managers in each of these locations must balance a number of constraints. One is that demand is not fully known: the actual demand for water can vary because of large numbers of factors, most notably temperature but potentially also included other factors that are either difficult to know or unknowable. Physical constraints- water availability- are minimized by the existence of Lake Mead; although the water level in Lake Mead has been dropping consistently, water is physically available to serve the entire demand. However, institutional constraints impose additional difficulties. USBR requires a schedule of water requests in advance; this must be delivered to USBR in December and must indicate the expected deliveries for the subsequent calendar year. CAP is the direct contact to USBR, and therefore must coordinate with its subcontractors on their anticipated demands. The result is that subcontractors must submit a monthly schedule of anticipated need for CAP water by October 1st for the subsequent January-December year.

The annual total requested is a hard limit: subcontractors cannot receive more water than they originally scheduled for the year, even if demand is higher than anticipated. If demand is less than anticipated, water that was originally scheduled but not delivered incurs a charge anyway; this is at a lower rate, but still significant. The result is that managers can allow their monthly totals to diverge from the scheduled amounts but need to bring them back in line by the end of the calendar year. This need provides a motivation for a system of exchange: if managers with shortfalls can acquire water from managers with surpluses, both will benefit.

Simulating a system of exchange

We are interested in simulating a system of hypothetical water exchanges that address this need. To construct our simulation, we take this situation and make three additional assumptions. The first is expressly unrealistic: we assume that the participants in this system are only concerned with CAP water. In reality a shortfall in CAP water could be met from other portions of a subcontractor's portfolio, for example from groundwater, while an overage would likely be dealt with by purchasing less from another source. However, for our demonstration we assume actors without these additional options. We then impose two additional conditions. The first is that surplus water can be offered to other subcontractors and that a subcontractor experiencing a shortage could acquire water offered from others' surpluses via the CAP central adjudicator. The second is that the mechanism for distributing this water at any specific time is to distribute the total offered surplus from all actors proportionally to the total requested shortfalls. This first condition creates the water market and the second condition allows for a simple ruleset to effect that market. Reflecting, somewhat, the actual legal and contractual situation among CAP subcontractors, direct exchanges from one subcontractor to another are prohibited; our simulated exchanges are required to go through the central adjudicator (represented in our simulation by the CAP).

We introduce a (potentially) fair exchange by assuming that all exchanged amounts are allocated according to a strict proportional rule. In the simplest case where the amounts requested exactly equal the amounts offered, all those offering give 100% of their offer, and all those requesting will receive 100% of their request. However, if more or less is requested than is offered, the distribution is impartially and automatically apportioned: If requests total only 90% of offers, then all requests are filled, but all those offering are permitted to give only 90% of their offer. If offers total only 90% of requests, then all water offered is allowed to be given, but all those requesting receive only 90% of their requests. This is true even if the amounts offered or requested vary widely, such that one user offers much more than others or one user requests much more. Actors are allowed to make offers and requests once per month.

We note that this simulated system of exchange is only one of many that could be imagined; we select it because it seems to meet a prima facie notion of fairness: all actors have equal opportunity to participate, and all allocations are done according to an open rule that contains no apparent bias for or against any category of participant.

Additional details about the simulation are provided in supplementary material. The simulation code itself is available at https://www.comses.net/codebases/fb969ece-f8b2-46b0-8bdf-782cd1507545/releases/1.0.0/.

<u>Strategic and Dynamic Agents</u>

The agents in the simulation are endowed with a strategy by which they calculate whether they will request or offer water, and in what amounts. Conceptually, when the agent is given the opportunity to exchange water, it assesses the usage to-date and projects its anticipated total usage to the end of the current year. If that falls below a threshold with respect to the scheduled water (e.g., less than 95% of the water requested), the agent anticipates a surplus; if it falls above a threshold (e.g. more than 105% of the water requested), it will anticipate a shortage. It can then make an offer of water or a request; the amount offered will be a fraction of the calculated surplus, while the amount requested will be a fraction of the expected shortage. For example, an agent's strategy may be to offer half of any surplus but request 120% of any shortfall.

To make the simulation dynamic, the agents are allowed at the end of the simulation year to assess their strategies and adjust them. For the results presented here the threshold values are held constant, but the percentages to offer and request are changed. Conceptually this is done simply: if an agent offered water but ended the year with a shortage, it should offer less next time; if it offered water but still ended with a surplus, it should offer more; if it requested water but ended with a shortfall, it should request more; if it requested water and then ended with a surplus, it should request less. The adjustment of strategies along these two dimensions we refer to as movement through a 'strategy space' comprised of these two axes.

It is key to remember, however, that the success or failure of any strategy depends not only on the water demand and on an agent's strategy in isolation, but on the strategies of the other agents. Requesting water is futile if no other agent offers a surplus; offering water is equally ineffective if no other agent is requesting it.

To study the simulation as an adaptive and dynamic system, we allow the simulation to proceed through hundreds of iterations. Because each iteration is based on a calendar year, the outcome of a given run is unrealistic in its specifics. However, the dynamics that are observed as the simulation progresses through this unrealistic time illustrate the forces that act on agents at any given time. We additionally start the simulation from different points in the strategy space, such that the collection of actors represents wide variations in the collections of strategies being used. For example, we can start the simulation with all agents offering large percentages of any surplus but requesting only small percentages of shortfalls; alternatively, we can reverse this, so that requests are large and offers small. We can also mix the strategies so that all ranges are represented. It is not possible to explore all possible combinations of all possible strategies; there are too many to be computationally tractable. However, by starting the simulation in ways that represent different possible balances among strategies, we can derive a map of the overall behavior of the simulation and infer its dynamics in all possible cases.

This simulation structure allows us to capture the institutional constraints under which management decisions are made, and the social setting in which these decisions are played out. This ability to capture the social milieu and its changing dynamics is unique to ABM. We additionally note that the dynamics that result may be difficult to anticipate, or to capture in another analytical framework. We propose that this applies more generally, so that the richness of a wide variety of non-market approaches, their long-term dynamics (e.g., per Layton's framework), and their social implications (such as shifting norms) can be captured.

Some representative results

For all runs presented here we use 14 interacting agents; this number is used because we have data on 14 subcontractors in the Phoenix area and have applied these data in other projects. To capture the impact of differences among agents, we craft simulation runs in which we vary the population sizes, and hence the water demands of the individual actors. For baseline runs we assume that all actors have identical population sizes. In theory, the case in which all actors are identical need not lead to all actors adopting the same strategy: it is conceivable, for example, that a small group of 'high offerers' might be balanced by a large group of 'low offerers'; alternatively, the actors could simply drift through the strategy space. However, a more intuitive idea would be that all actors experience the same 'forces', and hence all the actors move through the strategy space in the same ways and eventually arrive at a common strategy, regardless of the starting points. We omit these results here, but the simulation can be run to show that this intuition is correct: if all subcontractors are the same, they converge on a single, common strategy.

The system is changed, however, when we allow the subcontractors to have different population sizes. For an initial set of such runs we assume the 14 subcontractors have population sizes of 2500, 250000, or 1 million, forming groups of small, medium, and large populations. Figure 1 shows the results for the 'small' and 'medium' cities. 'Small' cities are shown with dark blue trails moving from starting positions to yellow points marking the end position; medium cities are shown with light blue trails leading to red end points. Runs were conducted by starting all small, medium, and large cities at one of 3 points along each strategy axis (hence 9 x 9 x 9 = 729 starting combinations). Each of the 9 graphs in the Figure shows all of the results for the 81 combinations with the small cities at one of the 9 starting points; the data for the medium cities reflects the combinations for the 9 starting points within those 81. The key insight is that, regardless of the initial starting conditions, the system moves toward a state in which the small populations (yellow) arrive at a strategy of 0.45 offer, 0.65 return, while the medium populations (red) arrive at a different strategy, 0.55 offer, 0.85 return. Figure 2 shows the endpoints for these and for the large populations. Note that the large populations moved much further, both offering and requesting large values in ways that the smaller groups of cities do not.

Finally, we present a pair of graphs that illustrates the results when realistic population sizes are used (Figure 3). We draw populations from 14 of the subcontractors from the Phoenix area. The simulation dynamically moves toward a state in which each subcontractor employs a distinct strategy: smaller subcontractors are more conservative in both offering and requesting water, while larger subcontractors generally offer and request more, and the collection arrays itself along a continuum within the strategy space. This state is stable: deviations away from the strategy will be short-lived as the forces acting on this actor will push it back toward the stable position.

Dynamic Systems and Conceptions of Fairness

The simulation, however, shows that there are implications of different kinds of fairness. We can speculate that in our simulated system of exchanges, perceptions of the system's fairness might depend on the subcontractor's position within the system. A subcontractor adopting a strategy outside of the points of stability revealed by the simulation will experience a force pushing toward a different strategy. This may be true even if the initial strategy is the same one adopted by another subcontractor who, because that subcontractor is a different size, does not experience this same force.

In the context of negotiations over water allocation, it is possible that these differences might be recognized and understood correctly. However, in the absence of the system-level understanding provided by the ABM, they might be misunderstood, and instead attributed not to the system's dynamics but to the personalities of the individuals making the decisions. It is easy to envision that some subcontractors may feel a system works less well for themselves than it does for others, or that others are adopting strategies that are unfair or injurious to their interests, and, following this, taking actions that are retaliatory or punitive and that lead to less-than-optimal solutions not only for themselves but for the entire system.

Conclusions

These are speculations, but we believe they are reflective of the challenges faced by managers and institutions when water allocation systems are created, adjusted, or (re-)negotiated. We propose that applying ABM with dynamic agents sheds useful light on these issues and could be helpfully included in the process of designing these systems. All water allocation systems, including market-based systems, will contain rich complexity (Garrick & Svensson, 2018) that ABM can approach. Although we have not done so here, it is possible to endow agents in an agent-based model with much richer portfolios and more complex decision-making skills. Agents in such models could not only have the option to obtain water from different sources in their portfolios, but to trade water rights in their portfolios or invest in and acquire new water sources or implement water conservation strategies among their constituents. The institutional rules by which they acquire and exchange water can be modeled in equally rich detail. We note that the same ABM framework presented here has also been used to model household-level water consumption activities and the response to demand-suppression campaigns (Ozik et al., 2014); it can be linked with this management-level simulation and with regional hydrological models (Murphy et al., 2015) to form an integrated model of both management-level and consumer-level decision-making.

Exploring all of the potential of such models for any specific context would require an extensive and comprehensive research project, one that would most effectively be done in cooperation with the stakeholders in the system, who would not only be able to provide the richest data but also the best insights into the system, and, as well, would be the most likely to benefit from the model itself. In this scenario, ABM could prove to be an important adjunct to the process of designing, evaluating, and operating water allocation institutions. In an ABM the implications of design choices could be explored, and proposed solutions that seem to be procedurally and distributively fair could be explored under a wide range of circumstances, including both changing social and environmental aspects. Stakeholders could be shown how their own decisions constrain the options of others, and how the decisions of others are outcomes of their situations. In this way, the rich historical context in which a water allocation institution is established or modified can be rigorously explored, and better, more efficient, more effective systems in which all participants are satisfied that their interests are represented.

Funding Information

This material is based upon work supported by the National Science Foundation under Grant No. BCS-1114851. The authors have declared no conflicts of interest for this article.

Research Resources

Data on water usage in southern Arizona provided by Tucson Water was used in portions of this study.

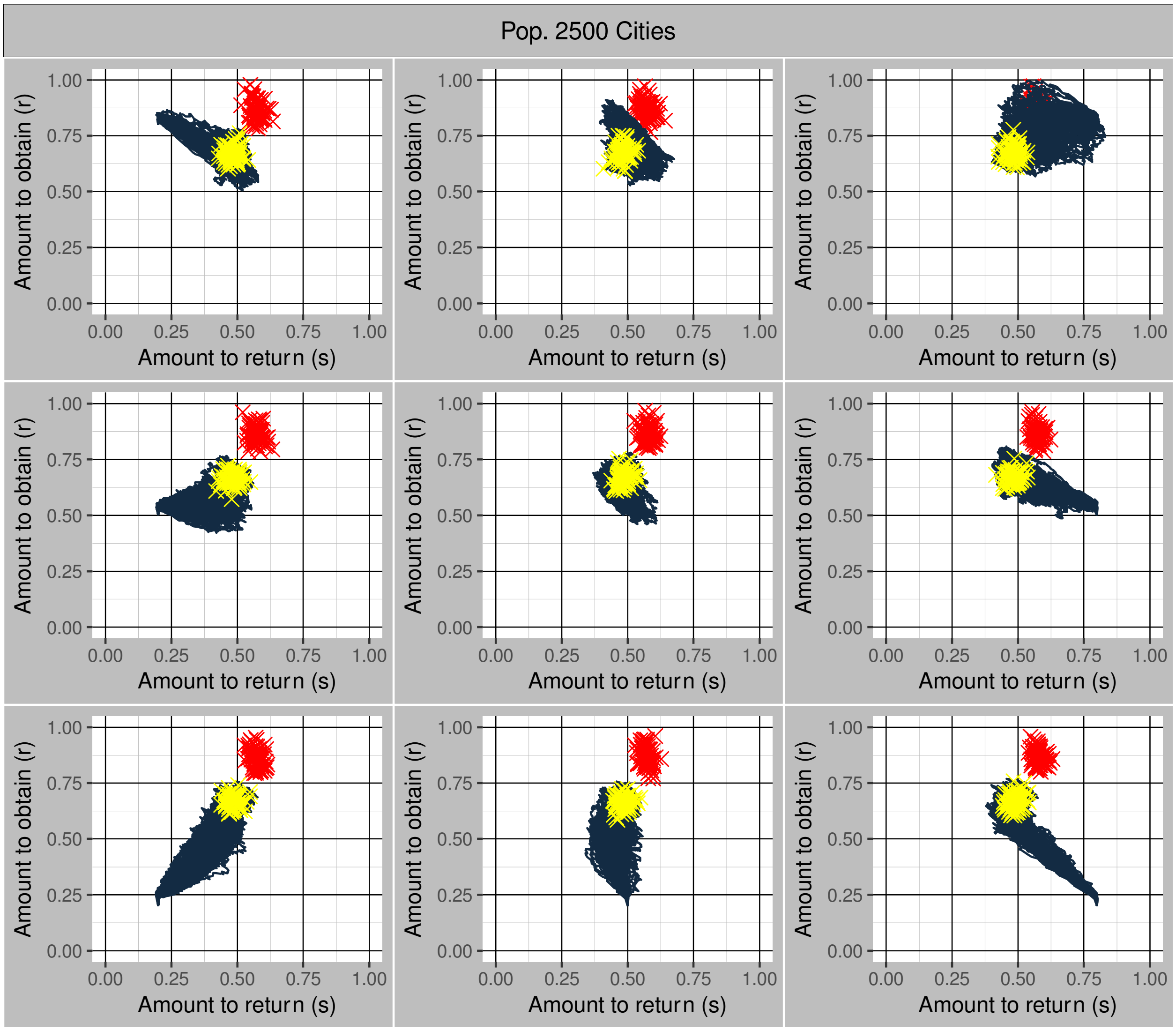

Pop. 2500 Cities
Amount to obtain (r)
Amount to return (s)
0.00
0.25
0.50
0.75
1.00

Figure 1.

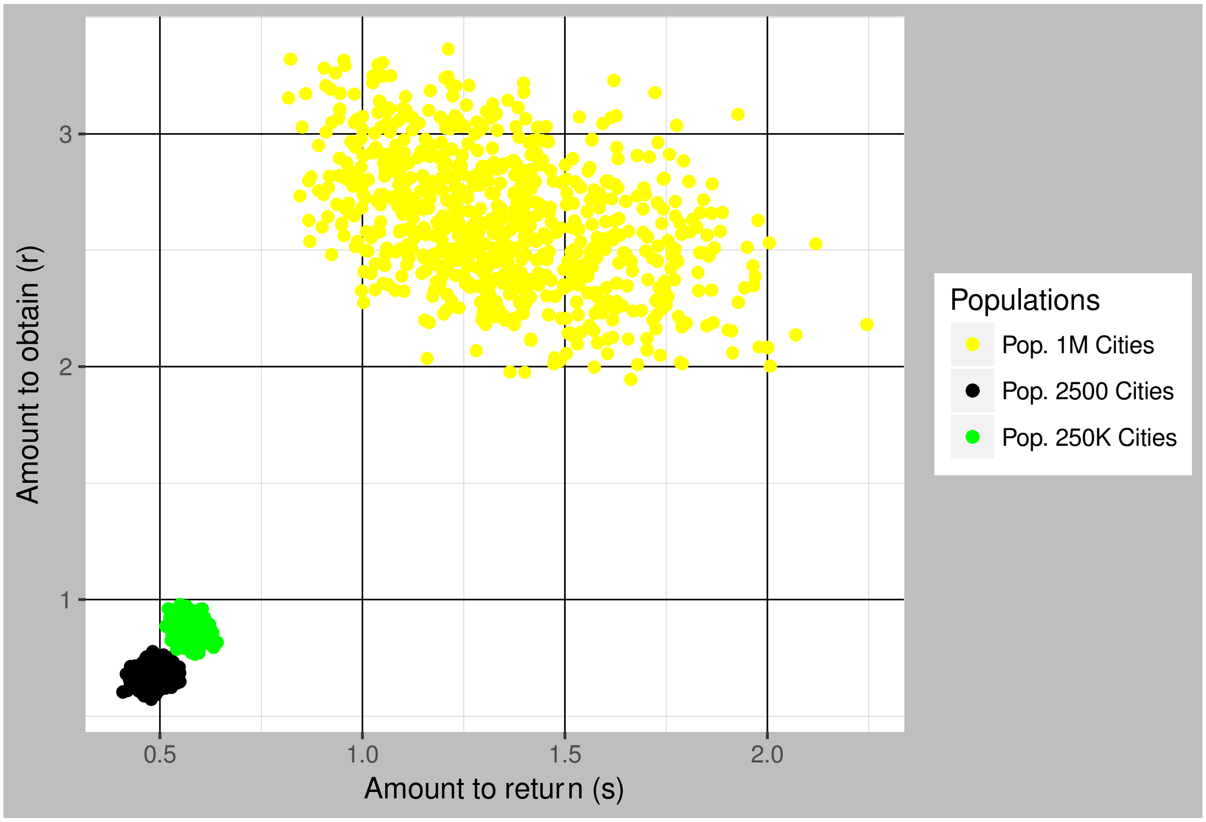

Amount to obtain (r)
3
2
1
0.5
1.0
1.5
2.0
Amount to return (s)
Populations
Pop. 1M Cities
Pop. 2500 Cities
Pop. 250K Cities

Figure 2

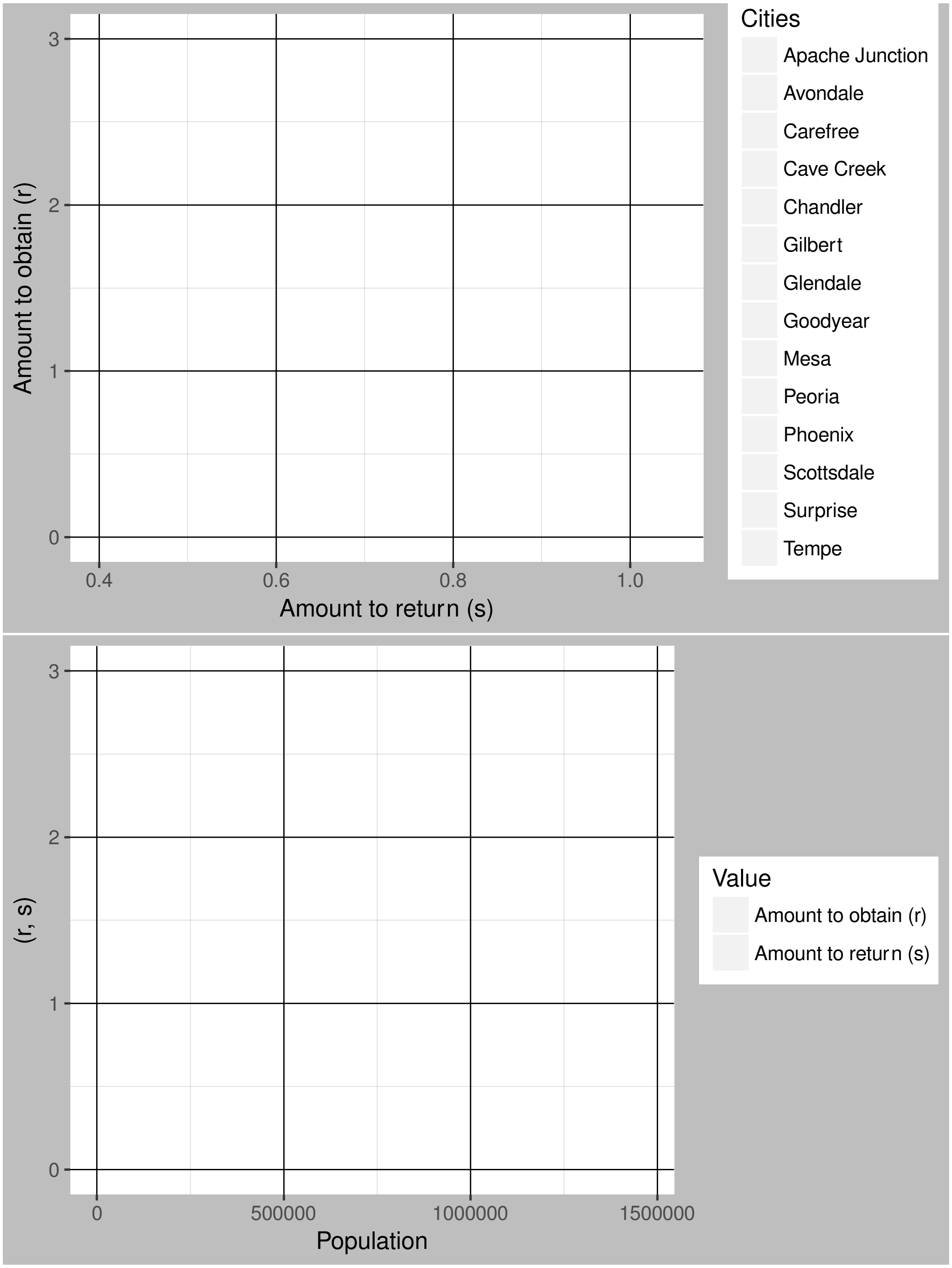

Cities
Apache Junction
Avondale
Carefree
Cave Creek
Chandler
Gilbert
Glendale
Goodyear
Mesa
Peoria
Phoenix
Scottsdale
Surprise
Tempe
Amount to obtain (r)
Amount to return (s)
0.4
0.6
0.8
1.0
0
1
2
3
(r, s)
Population
0
500000
1000000
1500000
Value
Amount to obtain (r)
Amount to return (s)

Figure 3

Works Cited

Appadurai, A. (2011). Introduction: Commodities and the politics of value. In *The Social Life of Things: Commodities in Cultural Perspective* (pp. 3–63). Cambridge: Cambridge University Press.

Athanasiadis, I. N. (2005). A Hybrid Agent-Based Model for Estimating Residential Water Demand. *SIMULATION*, *81*(3), 175–187. https://doi.org/10.1177/0037549705053172

Bakker, K. (2007). The “Commons” Versus the “Commodity”: Alter-globalization, Anti-privatization and the Human Right to Water in the Global South. *Antipode*, *39*(3), 430–455. https://doi.org/10.1111/j.1467-8330.2007.00534.x

Bohensky, E. (2006). *A Social-Ecological Systems Perspective on Water Management in South Africa*. University of Pretoria, Pretoria, South Africa.

Bohensky, E. (2013). WaterScape (Version 1.0.0). Retrieved March 15, 2018, from https://www.comses.net/codebases/2880/releases/1.0.0/

Cohon, J. L., & Marks, D. H. (1975). A review and evaluation of multiobjective programing techniques. *Water Resources Research*, *11*(2), 208–220. https://doi.org/10.1029/WR011i002p00208

Decision Center for a Desert City. (2017). WaterSim. Retrieved December 16, 2017, from Decision Center for a Desert City website: https://sustainability.asu.edu/dcdc/watersim/

Epstein, J. M. (1999). Agent-based computational models and generative social science. *Complexity*, *4*(5), 41–60. https://doi.org/10.1002/(SICI)1099-0526(199905/06)4:5<41::AID-CPLX9>3.0.CO;2-F

Epstein, J. M. (2006). *Generative social science: Studies in agent-based computational modeling*. Princeton: Princeton University Press.

Epstein, J. M., & Axtell, R. L. (1996). *Growing Artificial Societies: Social Science from the Bottom Up* (First Edition). A Bradford Book.

Ferguson, J. L., Ellen, P. S., & Bearden, W. O. (2014). Procedural and Distributive Fairness: Determinants of Overall Price Fairness. *Journal of Business Ethics*, *121*(2), 217–231. https://doi.org/10.1007/s10551-013-1694-2

Garrick, D., & Svensson, J. (2018). *Political Economy of Water Markets: 40 Years of Debates, Experiments and Lessons Learned - Oxford Handbooks*. 36.

Gleick, P. H. (1998). The human right to water. *Water Policy*, *1*(5), 487–503.

Howe, C. W. (2005). The Functions, Impacts and Effectiveness of Water Pricing: Evidence from the United States and Canada. *International Journal of Water Resources Development*, *21*(1), 43–53. https://doi.org/10.1080/0790062042000316811

Kock, B. E. (2008). *Agent-based models of socio-hydrological systems for exploring the institutional dynamics of water resources conflict* (Massachusetts Institute of Technology). Retrieved from https://dspace.mit.edu/handle/1721.1/44199

Kopytov, I. (2011). The Cultural Biography of Things: Commoditization as Process. In *The Social Life of Things: Commodities in Cultural Perspective* (pp. 64–91). Cambridge: Cambridge University Press.

Lansing, J. S. (2003). Complex Adaptive Systems. *Annual Review of Anthropology*, *32*(1), 183–204. https://doi.org/10.1146/annurev.anthro.32.061002.093440

Layton, R. A. (2015). Formation, Growth, and Adaptive Change in Marketing Systems. *Journal of Macromarketing*, *35*(3), 302–319. https://doi.org/10.1177/0276146714550314

Miller, J. H., & Page, S. E. (2009). *Complex Adaptive Systems: An Introduction to Computational Models of Social Life*. Princeton University Press.

Murphy, J., Ozik, J., Collier, N., Altaweel, M., Lammers, R., Kliskey, A., … Williams, P. (2014). Water Relationships in the U.S. Southwest: Characterizing Water Management Networks Using Natural Language Processing. *Water*, *6*(6), 1601–1641. https://doi.org/10.3390/w6061601

Murphy, J. T., Ozik, J., Collier, N. T., Altaweel, M., Lammers, R. B., Prusevich, A. A., … Alessa, L. (2015, December 6). *Simulating Regional Hydrology and Water Management: An Integrated Agent-Based Approach*. Presented at the Winter Simulation Conference, Huntington Beach, CA.

Ostrom, E. (2005). *Understanding institutional diversity*. Princeton: Princeton University Press.

Ostrom, E. (2015). *Governing the commons: The evolution of institutions for collective action*. Cambridge, United Kingdom: Cambridge Univ Press.

Ozik, J., Collier, N., Murphy, J., Altaweel, M., Lammers, R. B., Prusevich, A. A., … Alessa, L. (2014). Simulating Water, Individuals, and Management Using a Coupled and Distributed Approach. In A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, & J. A. Miller (Eds.), *Proceedings of the 2014 Winter Simulation Conference* (pp. 1120–1131). Retrieved from informs-sim.org/wsc14papers/includes/files/100.pdf

Prendergast, C. (2016). The Allocation of Food to Food Banks. *EAI Endorsed Trans. Serious Games*, *3*(10), e4.

Prendergast, C. (2017). How Food Banks Use Markets to Feed the Poor. *Journal of Economic Perspectives*, *31*(4), 145–162. https://doi.org/10.1257/jep.31.4.145

Reed, P. M., Hadka, D., Herman, J. D., Kasprzyk, J. R., & Kollat, J. B. (2013). Evolutionary multiobjective optimization in water resources: The past, present, and future. *Advances in Water Resources*, *51*, 438–456. https://doi.org/10.1016/j.advwatres.2012.01.005

Sridharan, S., Barrington, D. J., & Saunders, S. G. (2015). Water Exchange Systems. In J. Bartram (Ed.), *Routledge handbook of water and health* (pp. 498–506). London: Routledge.

The European Parliament and the Council of the European Union. (2000, October 23). *Directive 2000/60/EC of the European Parliament and of the Council: Establishing a framework for community action in the field of water policy*. Retrieved from http://eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0004.02/DOC_1&format=PDF

United Nations General Assembly. (2010, July). *Resolution A/RES/64/292: General Comment No. 15. The right to water.* Retrieved from http://www.un.org/es/comun/docs/?symbol=A/RES/64/292&lang=E

U.S. Bureau of Reclamation. (1922). *Colorado River Compact*. Retrieved from https://www.usbr.gov/lc/region/pao/pdfiles/crcompct.pdf

U.S. Bureau of Reclamation. (1928). Boulder Canyon Project Act. Retrieved March 16, 2018, from https://www.usbr.gov/lc/region/g1000/pdfiles/bcpact.pdf

White, D. D. (2013). Framing Water Sustainability in an Environmental Decision Support System. *Society & Natural Resources*, *26*(11), 1365–1373. https://doi.org/10.1080/08941920.2013.788401

Withycombe Keeler, L., Wiek, A., White, D. D., & Sampson, D. A. (2015). Linking stakeholder survey, scenario analysis, and simulation modeling to explore the long-term impacts of regional water governance regimes. *Environmental Science & Policy*, *48*, 237–249. https://doi.org/10.1016/j.envsci.2015.01.006

Wutich, A. (2009). Water Scarcity and the Sustainability of a Common Pool Resource Institution in the Urban Andes. *Human Ecology*, *37*(2), 179–192. https://doi.org/10.1007/s10745-009-9227-4

Wutich, A. (2011). THE MORAL ECONOMY OF WATER REEXAMINED: Reciprocity, Water Insecurity, and Urban Survival in Cochabamba, Bolivia. *Journal of Anthropological Research*, *67*(1), 5–26. https://doi.org/10.3998/jar.0521004.0067.102

Wutich, Amber, J. R., Brewis, A., Sigurdsson, S., Stotts, R., & York, A. (2013). Fairness and the Human Right to Water. In *The Social Life of Water:* (pp. 220–238). New York: Berghahn Books.