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SIMULATING REGIONAL HYDROLOGY AND WATER MANAGEMENT: AN INTEGRATED AGENT-BASED APPROACH

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ABSTRACT

Water management is crucial to all societies. In addition to the technical challenges of moving large volumes of water from often distant sources to the populations that use them, water management entails a social challenge as well. In this paper we present a linked simulation framework in which a large-scale hydrological Water Balance Model (WBM) is linked to an Agent-Based Model (ABM) in which agents represent urban water managers. We present a test case in which agents plan individual water schedules to meet their consumers' needs, and optionally can interact when scheduled amounts fall short of actual demand. The simulation framework allows us to examine the impact of these relationships on the larger hydrology of the region, under different policy structures and water stress. We present a case study based on water management in Phoenix, Arizona, along the Central Arizona Project (CAP) canal.

1 INTRODUCTION

Water is crucial to life and central to human activities. As individuals we must consume water to survive, and collectively we use water for agriculture, energy, industry, transportation, and many other purposes. Human societies have managed water since their beginnings, and while modern societies have advanced technology with which to move and use water, the centrality of water, and – increasingly, in many areas – its scarcity, make water management more than a technical challenge: it is equally a social challenge.

The southwestern United States is an area in which water management has been achieved technologically through extensive infrastructure investment; this has reached extraordinary scales, as water is diverted and moved across large states and throughout the region. Equally impressive is the social infrastructure: the complex collection of laws, rights, and economic components that regulate who gets water, when, and for what purposes. This social picture is difficult to understand, but crucial to manage: cooperation and conflict among different parties who must share water as a resource can shape the trajectories of cities and states. Policies are sought that lead to beneficial outcomes, but the policy instruments are limited by the purviews of the institutions that can make them (be they geographically bounded or limited to specific domains), and actors and entities that manage and use water exist at multiple crosscutting levels. Hence the impacts of policies are difficult to assess and the management of the resource that will result from these is challenging to foresee. Moreover, the behavior of these complex systems under stresses, such as extreme or prolonged water shortages, is difficult to anticipate, and the problems that result can be hard to ameliorate.

We present a simulation framework that is intended to enable exploration of the complex dynamics that inhere in a water management system. Our approach joins a hydrological simulation capable of tracking the movement of water through physical processes across continental and regional scales with a simulation of human decision-making in the form of water management, from regional to local and individual scales. The preliminary work presented here discusses the linkage between two components – social and physical – of the model and the concomitant ability to place local decisions in their regional contexts and examine their wider effects.

2 BACKGROUND

Many areas in the U.S. southwest are facing water shortages, and 2015 is projected to continue to be dry (National Weather Service 2015). Management of water during a time of shortage is essentially a question of determining who will get the water that is available and when; while there are technological constraints on the movement of water, it is, fundamentally, a social problem first.

2.1 Water Issues in the Southwest

Water management in the US southwest is characterized by a myriad of adjacent and overlapping systems (Kenney 1997). Federal, state, and local institutions manage different components of any area’s water resources, and at each level multiple institutions may be responsible for different aspects of water management. Private entities including corporations and non-profit organizations can participate in the management process through advisory roles, activism, or investment and ownership. Water management institutions at local levels are frequently descendants of entities established many years ago, when the context of water management, including population sizes and relationships with other cities and towns, was quite different. In some of these cases disparate original institutions have been subsumed under centralized entities; in other cases, peer institutions continue to manage water even as their once-separate interests increasingly interconnect (Murphy et al. 2014).

The impacts of this structure are a topic of interest to social scientists researching water management. Such research focuses on whether the structural characteristics of management impact the capability of the overall system to operate effectively and to withstand challenges or shocks (over both short and long time scales). It might seem that a single, unified system would carry intrinsic advantages over the conflicting and contested system that is actually in place. However, the apparent inefficiency in a fragmented system, which can have not only redundancy but also competing interests, can be balanced by less intuitive strengths. Redundancy can provide resilience, where a multiplicity of competing viewpoints can generate solutions that might otherwise fail to be recognized (Huitema et al. 2009). Neither system is necessarily better than the other in an abstract sense; the performance of each must be measured against different levels of variability among the range of possible environmental stressors. The model described here is intended to be used to explore these multiple possibilities.

2.2 Water in the Phoenix Metropolitan Area

Our case study area is Phoenix, Arizona. As of 2010 (ADWR 2010), approximately 31% of water used across all sectors (including agricultural, industrial, and residential) in the Phoenix metropolitan area (PMA) comes from groundwater (wells); surface water accounts for 38%, primarily from the Salt River, which rises in the east and flows westward into Phoenix, joined by several tributaries along the way. The Salt River is dammed upstream of Phoenix and its waters are channeled and controlled; the entity in charge of this is the Salt River Project (SRP). About 30% of water used comes from the Colorado River. This water is brought to Phoenix by the Central Arizona Project (CAP) canal, which draws water out of Lake Havasu and uses a system of pumps, canals, and siphons to transport the water more than 240 km to Phoenix; the CAP canal continues beyond Phoenix and provides water to Tucson and its surrounding areas some 160 km to the south.

3 PREVIOUS WORK

3.1 Text Mining of Water Management Networks

Previous work by our team (Murphy et al. 2014) explored the feasibility of using text mining to discover networks of interactions among management institutions. Our approach used local news reporting to reflect public perceptions of water management and the structure of water management in four urban areas in the Colorado River Basin. The results of the text mining analyses demonstrated that automated natural language processing and network analyses could capture important structural differences between water systems in the four assessed areas. The differences reflected the different management strategies in these areas, from centralized to more fragmented systems, that had developed over the different water management histories. Different water management structures can result in differences in water management effectiveness under varying circumstances.

3.2 SWIM

The Simulating Water, Individuals, and Management (SWIM) model is an earlier version of our water consumption model (Ozik et al. 2014) which is extended in the work presented here. SWIM simulates residential water consumption at the household level. SWIM is an Agent-Based Model (ABM), wherein households are represented by individual software agents. Household agents are linked with their neighbors via non-geographic social networks that influence water consumptive patterns. These social influences are intentionally abstract: they can include either transmission of explicit conservation messages or implicit water use norms. For example, a household with a brown lawn in a neighborhood with lush green lawns might be receiving an implicit norm about water use; conversely, a household with a green lawn that sees its neighbors transition to xeric, desert-style landscaping, receives the opposite message. Rather than model lawn use and observation directly, we aggregate all possible water use messages into an abstract, ‘social influence’ variable. Thus all social influences are incorporated as weighted factors that can increase or decrease water consumption by households. In addition to influence from networks of friends, acquaintances, and neighbors, water prices, historical usage patterns, and exogenous factors (e.g., government policy) are represented, which also have associated weighted factors that influence water consumption. These are combined to generate total water demand (Ozik et al. 2014).

The model also incorporates water managers, who are agents that control the amount of water made available. The water manager behaviors also include a messaging capability by which managers can attempt to encourage conservation and curtail water consumption in periods where demand is too high. The variables that control this are messaging intensity, or how frequent and pervasive messages are sent to diminish water demand, and messaging effectiveness, which determines the effectiveness of specific informational campaigns.

3.3 WBM

The Water Balance/Water Transport Model (WBM) is a macro-scale hydrological simulation system used from global and regional to local spatial extents. It has been operated over a variety of gridded resolutions from 30 arc-minute (e.g. Wisser et al. 2010) to finer 120 m grid cells (Stewart et al. 2011). Precipitation and temperature are the principal drivers using historical data to determine the local physical processes such as evapotranspiration (Vorosmarty et al. 1998), snowmelt, as well as surface and subsurface flow. All processing in WBM is performed at daily time steps. The model tracks surface flow horizontally through cells linked via a directed acyclic network (Vorosmarty et al. 2000a) from upstream to downstream locations. Human activity impacts hydrology and is represented in a number of ways. The WBM includes an extensive database of dams and reservoirs, through which river flow is controlled. Irrigation also occurs: a global map of crops, both irrigated and non-irrigated, each with unique planting schedules drives water demand which is extracted from local runoff, rivers, reservoirs and via unsustainable groundwater mining to fill this demand (Wisser et al. 2008, 2009). A unique feature of the WBM is the ability to position inter-basin hydrological transfers in space and time (Lammers et al. 2013). These are points where water is transferred from one watershed or subwatershed to another using a specified origin, destination, start date, and transfer rules. The transfers are a time varying function of river flow in the donor cell; these can be used to represent long-distance canals.

The model has been applied to a wide variety of questions related to the hydrological cycle including global and regional water resource management (Vörösmarty et al. 2000b, 2005), regional irrigation impacts on climate (Douglas et al. 2006, Grogan et al. 2015), frozen ground (Rawlins et al. 2003) isotopic signatures (Fekete et al. 2006), and river temperature (Stewart et al. 2013).

4 ABM/WBM INTEGRATION

The rationale for integrating the WBM and the ABM has several aspects. From the WBM perspective, the ABM offers a way to include human decisions that are more accurate for a given region than the generalized proxies that the WBM natively includes. For example, the WBM uses a set of rules to govern dam releases based on dam function, capacity, and historical flows. But these rules are applied globally–that is, to all dams everywhere in the world. Regional variation, finer functional differences, and local constraints are ignored. The ABM offers a way to customize the operation of specific dams in a given region, and, moreover, to embed that operation in the local context in a way that is reactive to both physical and social conditions. The WBM includes proxy rules not only for dam operation but for a wide range of other human activities, including irrigation and urban water use; the ABM can substitute a dynamic simulated social system in place of these abstract and generalized rules.

From the ABM perspective, the WBM offers a way to enforce the constraints of the physical environment: it implements real-world hydrology in a way that the ABM, with its focus on human decision-making, does not. It allows us to situate water use of a simulated urban context within a larger physical hydrological context. This allows us to simulate the impacts of wider hydrological dynamics, e.g., an extended regional drought, on a specific city. The ABM can also be employed to simulate multiple interacting cities; the interactions occur via environmental mediation through each city's impact on the common hydrological system. By processing the impacts of one city and propagating these downstream, the WBM transmits these effects across the simulated region.

For the initial tests described here, the WBM runs on a server at the University of New Hampshire, while the ABM runs on a remote computer (a laptop typically run at Argonne National Laboratory) that connects to the WBM server. Our choice of method by which the two simulations can communicate was limited by the initial need to minimally impact the WBM code; we elected to use the ZeroMQ protocol (http://zeromq.org) because of its ease of implementation and flexibility in initiating the information exchange. The ABM initiates the exchange by sending a message with a tabular (CSV) format; the use of this format permitted easy implementation as well as easy inspection for verification purposes. (We note that this method of exchange is not maximally efficient; work is underway to port the linked WBM and ABM simulations to a common environment for running large-scale ensemble runs.) The values passed include: a specific latitude and longitude (lat/lon); an amount taken from the WBM from its 'surface flow' at this location; an amount taken from its 'groundwater pool' at this location; the change in storage for the ABM; and the amount of water passing outside the limits of the the simulation (e.g. returned to the atmosphere). On the first occasion for which the ABM is sending a row for any given lat/lon location, the values for all other columns other than lat/lon are zero.

The WBM replies to this with a table of its own. This table includes the WBM date; the original coordinates as sent by the ABM; the coordinates of the southwest and northeast corners of the WBM grid cell within which those coordinates fall, and that grid cell's unique WBM ID number and its area; the amount of flow available on the surface in that cell (in cubic meters per second); and the amount of groundwater available in that cell (in mm). The ABM is initially unaware of the resolution at which the WBM is being run; hence it sends a collection of coordinates that suit its needs first. However, in any given exchange, many of these coordinates may fall within a single WBM grid cell. If this is the case, the corresponding rows returned by the WBM will be identical except for the echo of the coordinates that the ABM provided. The ABM accepts this list and scans it for duplicate grid cell IDs. If duplicates are found, the corresponding ABM data structures are merged, and the ABM thereafter sends only one coordinate per WBM grid cell. This has proven to be an effective, automated method for bridging the differing resolutions. In subsequent exchanges the ABM request will include values for the amounts taken from 'surface flow', 'groundwater pool', the storage change, and the amount eliminated from the simulation. Negative values mean water is being returned to the WBM, while positive values mean water is flowing out of it. The WBM adjusts the values that it holds per grid cell to reflect these changes.

Additionally, the WBM can respond with information about the amount and kinds of crops being grown in each grid cell. Because much of water use, including use from the CAP canal, is agricultural, it is necessary to implement irrigation within the simulation. The WBM provides, for each crop: the kind of crop (via an ID number); the fraction of the total area of the grid cell that is under cultivation with this crop; the calculation of irrigation demand that the WBM has made; the soil moisture content available for that crop (in mm); and the fraction of the total possible soil moisture (field capacity) that this content represents. Multiple crops may be indicated by adding repetitions of these sets of columns without limit.

The ABM responses to this include two columns for each crop: one echoing the ID for the crop, and the second specifying the water to be placed onto the crop via irrigation, in mm. (Note that both the ABM and the WBM convert mm of water, in irrigation and soil moisture values, to volumes of water based on the area under cultivation as calculated from the area of the grid cell and the fraction of the cell under cultivation.) The initial occurrence of a crop in a given grid cell causes the ABM to instantiate 'field' and 'farmer' agents; farmer agents are connected to a water source within the given framework, allowing the ABM to direct the flow of water through the network from the CAP canal onto specific fields. When the WBM ceases to report on this crop in this grid cell, these data structures are destroyed in the ABM. Ideally the ABM would be able to control this irrigation; in practice, for now, the ABM accepts the demand already calculated by the WBM.

While the technical issues of integrating the ABM and the WBM were comparatively straightforward, the conceptual issues are more challenging. The central issues are, which components of the WBM's model are shared with the ABM, and how can this sharing ensure that the water balance in the WBM is not violated? A second concern is to ensure that the ABM provides functions for things that are needed by the WBM, but does not reproduce functions that are already performed by the WBM- the ABM should not try to do things that the WBM already does better.

Our strategy has been to give the ABM access to the stocks that the WBM uses- surface flow and groundwater flow- and to allow the ABM to take (or give) water to these stocks, while simultaneously disengaging the WBM's control over certain components that it normally governs. For example, when the WBM is solely responsible for agriculture in a given grid cell (such as inside the Colorado River basin but outside of the ABM domain), it makes a series of assumptions about the water needs for crops and the supplies of water available, as described above. When the ABM assumes control of the irrigation of a grid cell, these WBM functions are disengaged for that cell.

We note, however, that there remain future opportunities. One is to allow the WBM to perform the functions that represent crop development and water use, but to allow the ABM to manage multiple instances of crops within a single grid cell, and to maintain customized states for each one. For example, currently there can be only one ‘wheat’ crop in a given grid cell, but the ABM may wish to enable several farmers to grow crops independently (and with different watering schedules); for this, the ABM might provide the WBM with a list of the individual instances, and the WBM would perform its standard calculations on each one independently, accounting for their different states. A second opportunity is to allow the ABM to step into the role of managing dams. Currently the WBM uses generic rules to govern the flow of water out of reservoirs; an ABM could manage a reservoir based on contextually-specific rules such as perceived water shortages, different ecosystem service valuations, etc.

5 CAP WATER MANAGERS

In our current work we move away from the simulation of individual households and toward the simulation of local and regional water management. We envision returning household agents to the higher-level simulation described here, the same technical architecture within the SWIM model is used, so that ultimately the more complex water managers described here will be able to interact with households, e.g. by directing the messaging campaigns that we explored in (Ozik et al. 2014). For the work presented here, however, we are interested in the social interplay among, and the behavior represented by, CAP management and CAP customers.

5.1 Managing the CAP Canal

Operation of the CAP canal is necessarily a social endeavor that requires planning and coordination on multiple time scales, from daily and hourly operations to monthly and annual plans. Although our simulation operates on a daily time step, the focus for our CAP management agents is on the monthly and annual scale. We base our water management algorithm on the real-world procedures for establishing these plans. Our interest is in two specific kinds of entities and their behavior with respect to CAP allocations: the CAP management and a class of CAP customers called CAP subcontractors.

CAP subcontractors hold the rights to order and purchase some amount of water from the CAP each year. Each October, CAP subcontractors are asked to provide schedules for their water deliveries for the following year; these are specified in deliveries per month. These subcontractors must therefore project their total CAP water demand for the year and the portions of that demand that they would receive in each month. Monthly demand can, of course, be strongly influenced by weather: the hot, dry months of summer lead to increased residential water use when compared to the cooler and wetter months in the winter and spring. Managers can use a mixture of historical demand records, climate and weather forecasts, and other sources of information to estimate their demands for each month throughout the year.

The CAP operators take this schedule and use it to plan their own operations for the subsequent year. This plan considers both the estimated demand from the subcontractors and other sources of information, such as planned maintenance outages and energy costs. This is eventually worked into an hour-by-hour plan of operation based on the monthly and annual demands of the CAP clients (Fox and Henning 2015).

However, projecting water demands is an inexact science, and actual water delivery is driven by actual demand. Deviations from the original plan at the system level can be buffered by water storage, especially in Lake Pleasant, a reservoir to the north of Phoenix that is used by the CAP canal while also being fed by the Verde River. However, for subcontractors, monthly demand can vary from projections. This demand, which may be driven directly by household consumption, is met by the CAP even if it exceeds the original month’s order. However, the annual total water delivered is limited by the original order. Hence, it is commonly the case that adjustments to the orders must be made during the course of the year. If a subcontractor sees that the water delivered is exceeding the projections, and thus the water ordered will be insufficient to fulfill demand through the end of the year, that contractor can elect to pursue other sources of water to make up the difference in the later months. Some of these sources can be CAP water; others may come from other components of their water portfolios. Conversely, if a subcontractor sees that water delivered is falling short of projections, a petition to the CAP can be made to allow the water to be remarketed to other CAP customers. If the water can be remarketed, the original subcontracting entity will achieve a saving in that it will not be held accountable for the cost of water that is not delivered. However, if the water cannot be remarketed, the subcontractor is responsible for a portion of the cost even if the water is not actually delivered because the demand is less than projected.

5.2 The Implemented Algorithm

For full reproducibility of our algorithm, our code will be made available (URL pending). We implement the water management algorithm by constructing two classes of agents: an agent representing the CAP management (technically called the Central Arizona Water Conservation District, or CAWCD), and a simple CAP subcontractor agent. The CAWCD agent manages the drawing of water from the Colorado and the delivery to the subcontractors and other clients across the region. Each subcontractor agent must make two decisions, as described above: the specification in October of a monthly schedule for the subsequent year, and an assessment of projected shortfalls or excesses and requests for additional supplies or the remarketing of the surplus from the CAP management.

Our implementation of this is intentionally simple. For the initial annual water delivery request, subcontractors use a single value for Gallons Per Capita Per Day (GPD), multiplied by the population and scaled by the same seasonal adjustment that we use throughout the rest of the simulation. The GPD value is drawn from data (available at http://www.westernresourceadvocates.org) and unique to each subcontractor. All recorded and prospective values are set to the same initial values for each month.

Thereafter, as the simulation continues, actual demand is driven by seasonal climate adjustments (driven by attested weather data) and a noise factor (a multiplier randomly selected from a uniform distribution between 0.8 and 1.3 for the runs described). Subcontractors keep a record of monthly usage vs. the original monthly scheduled amount. Beginning in July and each month thereafter except December, subcontractors can assess whether they anticipate annual demand exceeding the requested supply, and if this is so, they can begin to request additional supplies from the CAP. Alternatively, they can also anticipate that supply will exceed demand, and if so they can begin to volunteer an amount to return to the CAP for remarketing. The rule for this is set to 5%: if the current running total of water used plus the remaining scheduled water is more than 5% of the remaining scheduled supply, more water is requested; the amount requested is 110% of the perceived shortfall. If the remaining scheduled supply is going to be short of the projected demand by 5%, 90% of the expected surplus is returned..

Each month, if there is a pool of excess water that subcontractors have asked CAP to remarket, and there is a set of subcontractors who are requesting additional water, CAP apportions the water among the potential recipients in one of two ways: First, if the total demand exceeds the supply, water is apportioned to the potential recipients in the proportions of the individual demands; alternatively, if the supply available exceeds demand, all demand is supplied, with amounts drawn from the pool of donors in proportion to the amount each donor offered. For the next year's annual schedule, subcontractors use the actual demand from the previous year (that is, the 12 months prior to the October 1st creation of the schedule, which will include November and December from the previous calendar year; when the second year is scheduled, this will still be drawn from the values used to initialize the simulation).

We note that the use of actual demand for the next year's schedule avoids some of the real complexity managers face: it does not incorporate weather/climate forecasts nor secular trends in demand (e.g., downward per capita usage, growth in population), nor other factors that might apply in the real-world case. We also note that we do not consider the cost in dollars to CAP subcontractors; CAP water pricing is determined by a combination of operating vs. delivery costs, but we avoid this by assuming that each subcontractor will minimize the discrepancy between water scheduled and water delivered. By avoiding this complexity we can focus on the WBM-ABM link and lay the groundwork for future simulations.

6 RESULTS

We present first the outcomes of the CAP subcontractor interactions, with two contrasting sets of results. In the first, the redistribution of excess is not permitted; in the second it is permitted as described above.

Figure 1 illustrates a simulation run in which redistribution is not permitted. The graph shows shortages in December for years 2003-2011, as fractions of the demand. Keeping in mind that the limit on a subcontractor's water use is the annual budget (not the monthly estimates), shortages in deliveries will occur at the end of the year; we show here December shortages as a fraction of December demand, but note that in cases where the December shortage is 100% there may also have been a November shortage.

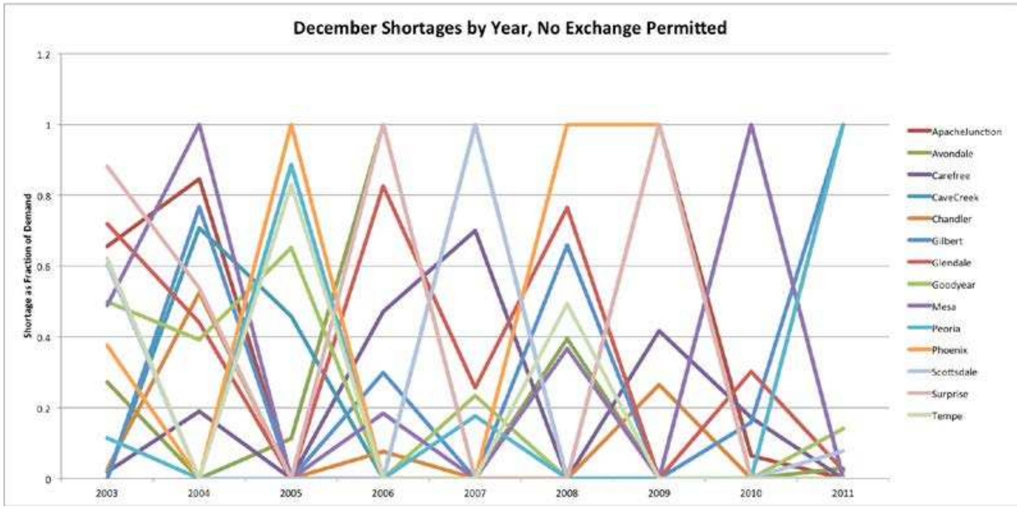


Figure 1: Simulated shortages in December by fraction of December demand, without exchanges.

Figure 2 illustrates an equivalent case, but in which redistribution is permitted. It is clear that permitting exchanges reduces the number of occurrences in which the allotment of water is exhausted before December. Of interest, however, is that in the no-sharing case, many entities experience a high shortfall in the initial years of the simulation (2003-2009), whereas for the case with exchanges permitted, this early period is not as marked by shortages, but later periods (2008-2010) are. Although the reasons for this are not fully understood, these dynamics are likely the result of the interplay among the exchanging agents (rather than, as it may appear, cumulative effects through time, which are minimal); the differences in performance are in keeping with our contention that alternative structural arrangements can perform differently against different kinds of stresses.

To understand the hydrologic impacts of these scenarios, we return to the data collected on water flow via the WBM. Figure 3 shows the baseline hydrology as calculated by the WBM.

Figure 4 presents a more direct comparison between a simplified baseline case in the WBM, in which no transfer of water from the Colorado takes place, and the case in which our CAP Subcontractors draw water from the CAP canal and return it to the landscape. In the figure, the purple and black pixels represent the negative values in the Colorado River itself, from which water is taken, and the orange pixels indicate locations that have received this water and thus have more than in the baseline run.

A long-term goal is to ensure that we are drawing the realistic amount of water from the CAP canal; for now we are simulating only a few CAP subcontractors and a subset of CAP customers. We tentatively implement additional demands in the simulation by drawing from the published data for CAP deliveries (available publicly at http://www.cap-az.com/), which is a full record of monthly amounts delivered. However, the exact location of delivery is not specified, nor is the purpose to which the water is put. We entered all years' CAP delivery data into a unified database and manually established canonical names for individual entities through time. Each delivery was coded for an inferred purpose as Municipal and Industrial (M&I), Agricultural, or Recharge. Delivery location was assigned based on best inference. Agricultural demand was excluded. All M&I water is returned to the WBM, but water used for recharge is not. Figure 5 represents the results. Most of the values are near zero, but near the Colorado River mouth they are cumulative and larger. These results will help refine both WBM and ABM algorithms.

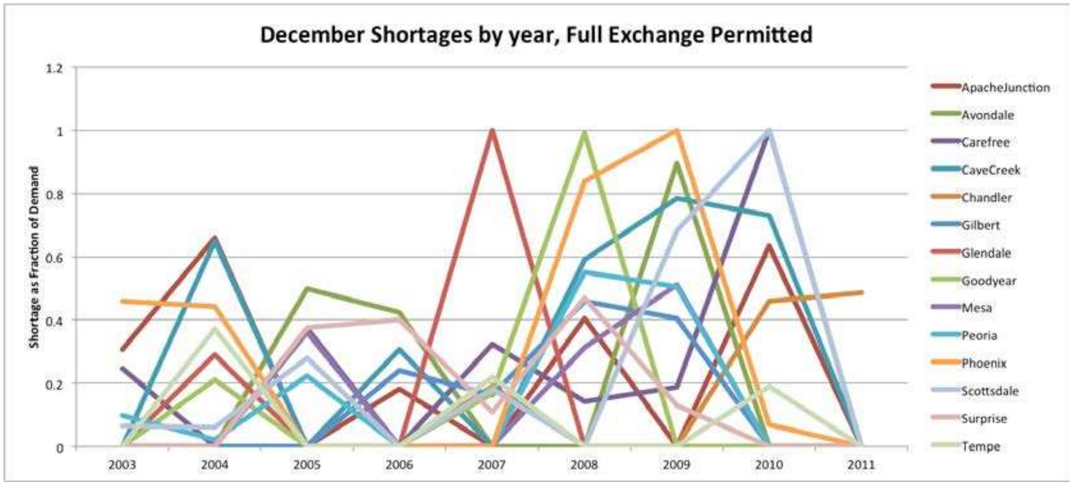


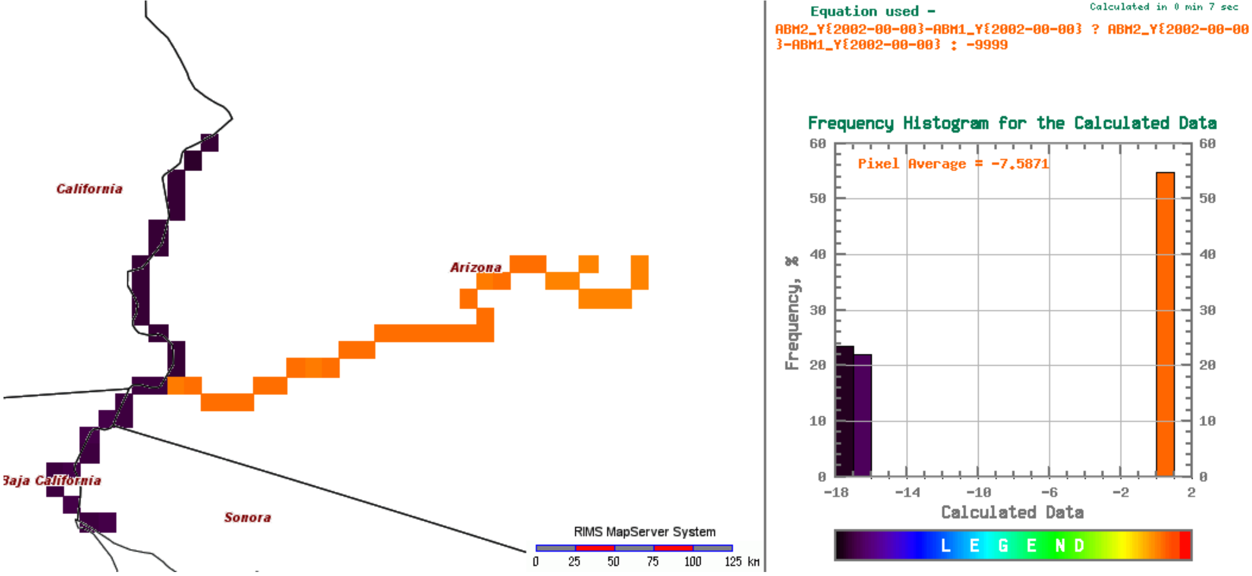
Figure 2: Simulated shortages as in Figure 1, with exchanges permitted.

Figure 3: Hydrology of baseline scenario. The bright green line represents the Colorado River, seen here with its tributaries, including the Salt and Gila rivers on which Phoenix sits.

7 DISCUSSION AND CONCLUSION

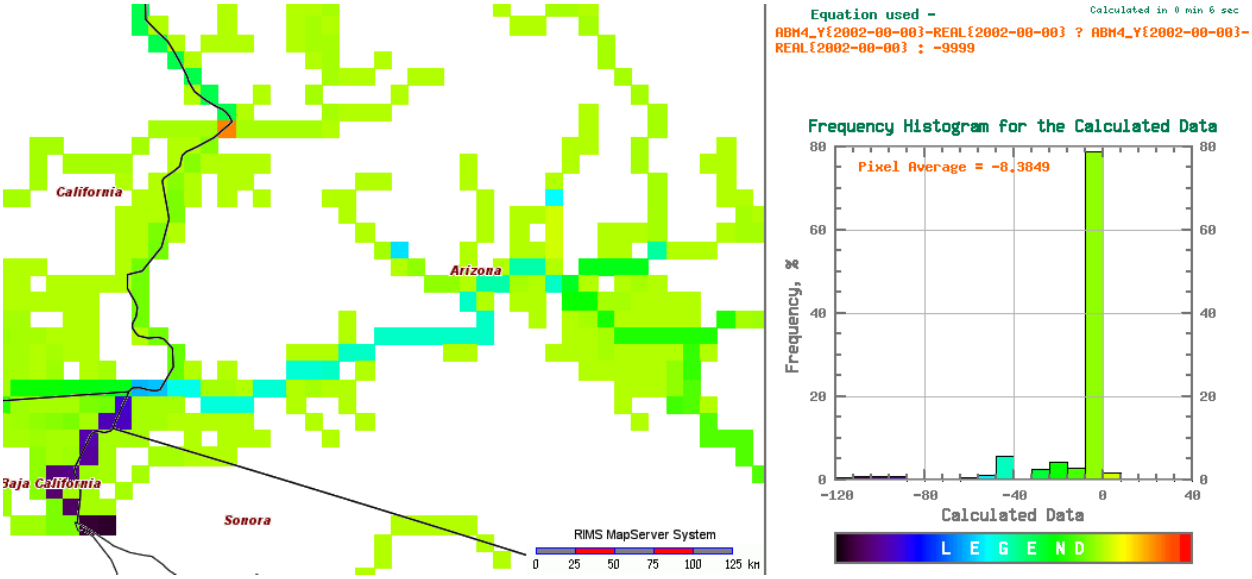
Future directions for this work include exploring a wide array of variations for the CAP subcontractor dynamics. The proportional allotment of surpluses to potential recipients is only one way that could be tried. Each alternative arrangement may perform differently, and benefit different kinds of actors (e.g. large vs. small), in the presence of different levels of environmental variance (noise). Actor attributes and strategies can be varied richly, and each manager may deal not only with the CAP but with the other water sources in its portfolio, including the Salt River Project and groundwater.

Our attempt here is not to display precise results against a real-world example, but to show that we can work toward this in the ABM and understand human impacts on regional hydrology. As water issues become more pressing worldwide, simulations that allow examination of alternative policies may play an increasing role in understanding which strategies can lead to workable, sustainable, and equitable results, and which may inadvertently lead to inefficiencies or vulnerabilities. Agent-based modeling offers the best way to engage with these questions; by linking an ABM with a regional physical hydrological model, we allow better understanding of the impacts of humans on the flow of water in a region, and the feedbacks from this altered flow to the societies that depend on it.



ABM2_Y{2002-00-00}-ABM1_Y{2002-00-00} ? ABM2_Y{2002-00-00}-ABM1_Y{2002-00-00} : -9999

Figure 4: Difference between a baseline run from the WBM with no water transfer from the Colorado to central Arizona, and a run in which CAP Subcontractors purchase water that is moved via the CAP Canal.



ABM4_Y{2002-00-00}-REAL{2002-00-00} ? ABM4_Y{2002-00-00}-REAL{2002-00-00} : -9999

Figure 5: Difference between a full WBM run, representing the most accurate hydrological reconstruction, and a run in which all forms of transfer implemented in the ABM are in place.

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REFERENCES

Arizona Department of Water Resources (ADWR). 2010. Demand and Supply Assessment 1985-2025, Phoenix Active Management Area. http://www.azwater.gov/AzDWR/WaterManagement/Assessments/default.htm#Phoenix. Downloaded 6/18/2015.

Douglas, E. M., D. Niyogi, S. Frolking, J. B. Yeluripati, R. A. Pielke, Sr., N. Niyogi, C. J. Vörösmarty, and U. C. Mohanty. 2006. Changes in Moisture and Energy Fluxes Due to Agricultural Land Use and Irrigation in the Indian Monsoon Belt. *Geophysical Research Letters* 33, L14403. doi:10.1029/2006GL026550.

Fekete, B. M., J. J. Gibson, P. Aggarwal, and C. J. Vörösmarty. 2006. Application of Isotope Tracers in Continental Scale Hydrological Modeling, *Journal of Hydrology 330*, 444-456.

Fox, J, and B. Henning (2015), Shortage Impacts to CAP Priority Pools and Customers. Colorado River Shortage Preparedness Workshop, April 22, 2015. Slides available at http://www.cap-az.com/index.php/colorado-river-shortage-preparedness-workshop, access 5/8/2015.

Grogan, D.S., F. Zhang, A. Prusevich, R.B. Lammers, D. Wisser, S. Glidden, C. Li, S. Frolking. (2015) Quantifying the Link Between Crop Production and Mined Groundwater Irrigation in China, *Science of The Total Environment* 511:161-175; doi:10.1016/j.scitotenv.2014.11.076.

Huitema, D., E. Mostert, W. Egas, S. Moellenkamp, C. Pahl-Wostl, and R. Yalcin. 2009. “Adaptive Water Governance: Assessing the Institutional Prescriptions of Adaptive (Co-) Management from a Governance Perspective and Defining a Research Agenda.” *Ecology & Society* 14 (1): 46.

Kenney, D.S. 1997. Resource Management at the Watershed Level: An Assessment of the Changing Federal Role in the Emerging Era of Community-Based Watershed Management. Report to the Wester Water Policy Review Advisory Commision, October, 1997.

Lammers, R.B., A. Prusevich, S. Frolking, and D. Grogan. 2013, Inter-basin Hydrological Transfers – Effects on Macro-Scale Water Resources, presentation at Global Water Systems Project (GWSP), Water in the Anthropocene: Challenges for Science and Governance, Bonn, Germany, May 21-24, 2013.

Murphy, J., J. Ozik, N. Collier, M. Altaweel, R. Lammers, A. Kliskey, L. Alessa, D. Cason, and P. Williams. 2014. “Water Relationships in the U.S. Southwest: Characterizing Water Management Networks Using Natural Language Processing.” *Water* 6 (6): 1601–41. doi:10.3390/w6061601.

National Weather Service (2015), U.S. Seasonal Drought Outlook, April 15-July 31 2015. http://www.cpc.ncep.noaa.gov/products/expert_assessment/sdo_summary.html, accessed 5/8/2015.

Ozik, J., N. Collier, J. T. Murphy, M. Altaweel, R. B. Lammers, A. A. Prusevich, A. Kliskey, and L. Alessa. 2014. “Simulating Water, Individuals, and Management Using a Coupled and Distributed Approach.” *Proceedings of the 2014 Winter Simulation Conference*, edited by A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, 1120-1131. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Rawlins M., R. Lammers, S. Frolking, B. Fekete, C. Vörösmarty. 2003, Simulating Pan-Arctic runoff with a macro-scale terrestrial water balance model. *Hydrological Processes,* 17:2521-2539.

Stewart, R.J., W.M. Wollheim, A. Miara, C.J. Vorosmarty, B. Fekete, R.B. Lammers, and B. Rosenzweig. 2013. Horizontal Cooling Towers: Riverine Ecosystem Services and the Fate of Thermoelectric Heat in the Contemporary Northeast U.S., *Environmental Research Letters* 8:025010, 10pp, doi:10.1088/1748-9326/8/2/025010.

Stewart, R. J., W. M. Wollheim, M. N. Gooseff, M. A. Briggs, J. M. Jacobs, B. J. Peterson, and C. S. Hopkinson. 2011. Separation of River Network–Scale Nitrogen Removal among the Main Channel and Two Transient Storage Compartments, *Water Resources Research* 47, W00J10, doi:10.1029/2010WR009896.

Vörösmarty C. J., E. M. Douglas, P.A. Green, C. Revenga. 2005. Geospatial Indicators of Emerging Water Stress: An application to Africa. *Ambio* 34: 230-236.

Vörösmarty C. J., P. Green, J. Salisbury, and R. Lammers. 2000b. Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science* 289:284–288.

Vörösmarty, C. J., B.M. Fekete, M. Meybeck and R.B. Lammers. 2000a. Global System of Rivers: Its Role in Organizing Continental Land Mass and Defining Land-to-Ocean Linkages, *Global Biogeochemical Cycles* 14(2), 599-621.

Vörösmarty C.J. , C.A. Federer, and A. Schloss. 1998. Potential Evapotranspiration Functions Compared on US Watersheds: Implications for Global-Scale Water Balance and Terrestrial Ecosystem Modeling, *Journal of Hydrolology 207*, 147-169.

Wisser D., B.M. Fekete, C.J. Vörösmarty, and A.H. Schumann. 2010. Reconstructing 20th century Global Hydrography: a Contribution to the Global Terrestrial Network- Hydrology (GTN-H), *Hydrology and Earth System Science* 14, 1-24.

Wisser D., S. Frolking, E.M. Douglas, B.M. Fekete, A.H. Schumann, and C.J. Vörösmarty. 2009. The Significance of Local Water Resources Captured in Small Reservoirs for Crop Production – A Global-Scale Analysis. *Journal of Hydrology* doi:10.1016/j.jhydrol.2009.07.032.

Wisser D., S. Frolking, E.M. Douglas, B.M. Fekete, C.J. Vörösmarty, and A.H. Schumann. 2008. Global Irrigation Water Demand: Variability and Uncertainties Arising from Agricultural and Climate Data Sets, *Geophysical Research Letters* 35, L24408, doi:10.1029/2008GL035296.

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