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Decision Insight into Stakeholder Conflict for ERN

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Decision Insight into Stakeholder Conflict for ERN

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Abstract

Participatory modeling has become an important tool in facilitating resource decision making and dispute resolution. Approaches to modeling that are commonly used in this context often do not adequately account for important human factors. Current techniques provide insights into how certain human activities and variables affect resource outcomes; however, they do not directly simulate the complex variables that shape how, why, and under what conditions different human agents behave in ways that affect resources and human interactions related to them. Current approaches also do not adequately reveal how the effects of individual decisions scale up to have systemic level effects in complex resource systems. This lack of integration prevents the development of more robust models to support decision making and dispute resolution processes. Development of integrated tools is further hampered by the fact that collection of primary data for decision-making modeling is costly and time consuming.

This project seeks to develop a new approach to resource modeling that incorporates both technical and behavioral modeling techniques into a single decision-making architecture. The modeling platform is enhanced by use of traditional and advanced processes and tools for expedited data capture. Specific objectives of the project are:

- 1) Develop a proof of concept for a new technical approach to resource modeling that combines the computational techniques of system dynamics and agent based modeling,

- 2) Develop an iterative, participatory modeling process supported with traditional and advance data capture techniques that may be utilized to facilitate decision making, dispute resolution, and collaborative learning processes, and
- 3) Examine potential applications of this technology and process.

The development of this decision support architecture included both the engineering of the technology and the development of a participatory method to build and apply the technology. Stakeholder interaction with the model and associated data capture was facilitated through two very different modes of engagement, one a standard interface involving radio buttons, slider bars, graphs and plots, while the other utilized an immersive serious gaming interface.

The decision support architecture developed through this project was piloted in the Middle Rio Grande Basin to examine how these tools might be utilized to promote enhanced understanding and decision-making in the context of complex water resource management issues. Potential applications of this architecture and its capacity to lead to enhanced understanding and decision-making was assessed through qualitative interviews with study participants who represented key stakeholders in the basin.

Acknowledgements

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Introduction and Background

Problem Statement

Formulating policies that motivate strategic changes in resource production, allocation and management is a key national challenge. The difficulty lies in selecting policy options that achieve particular goals while minimizing the potential for conflict. In fact, the success of policy decisions often hinges more on human factors than on the technical merits of a policy. *A priori* analysis is largely beyond the reach of current policy tools because: 1) there is a lack of integrated modeling of human factors and the environments in which they operate, and 2) collection of primary data for decision-making modeling is costly and time consuming.

Developing processes and tools for incorporating the human element as an integral component of technical analyses holds promise for bridging the gap between science and society. It also provides new insight into some of the most complex problems facing society today. The combined technical-behavioral model can foster a structured approach to participatory thinking and dialogue capable of promoting transparency in policy decision making.

Objective

To address these needs, we developed a simulation environment that integrates agent-based models of human decision-making behavior with traditional system dynamics (SD) models of resource constraints and economics. The modeling approaches were made more robust with the development and addition of advanced processes and tools for expedited data capture. This technical effort expands on traditional modeling/data capture to include factors such as stakeholder desires, needs, biases, and influence. Stakeholders in resource allocation decisions can include government authorities, consumers, commercial, and community interests.

By integrating these tools and processes together in one package, we are attempting to change the way decision-making models are constructed. The resultant socio-technical system models will aid development of candidate solution sets to streamline negotiation processes by providing perspective to all parties about decision trade-offs. They will also provide an early assessment methodology to identify potential conflicts. These insights have the potential to be applied in the form of assisted decision-making applications for customers in government and industry across a broad range of complex, uncertain, and potentially conflictive situations, including resource scarcity management, energy production, and nuclear waste storage.

A functioning tool linked to a case study with measureable results is necessary to demonstrate the applicability of this research concept to actual problems. For this purpose, an example problem involving water resource management in the Middle Rio Grande basin in New Mexico was adopted. While the system was developed for the particular problem of water allocation in the Middle Rio

Grande, it can easily be adapted and transferred to other equally challenging resource management and allocation problems.

Project Description

This project integrated two broad areas of science and engineering. One addressed issues in computer science, and the other focused on the application of the technology for use in decision support. The project incorporated spiral development of a computational model, a game engine and user interface, and a decision support system based on participatory modeling. The target sample problem was a complex resource allocation problem involving multiple stakeholders with a wide range of agendas, many of which were contradictory.

The computer science problem

From a computer science standpoint, we were interested in developing an integrated computational framework with agent-based and systems dynamics modeling. These two modeling approaches address different types of problems, both of which are present in a complex resource allocation decision. System dynamics “is a powerful methodology and computer simulation modeling technique for framing, understanding, and discussing complex issues and problems.”¹ It requires a holistic approach to understanding the target phenomenon. In agent-based modeling (ABM), a system is modeled as a collection of autonomous decision-making entities called agents. In ABM, “Each agent individually assesses its situation and makes decisions on the basis of a set of rules.”² Bonabeau explains that “ABM is a mindset more than a technology. The ABM mindset consists of describing a system from the perspective of its constituent units.”³

The two modeling types thus capture diametrically opposed perspectives on aspects of the same phenomenon: a holistic perspective in one case (system dynamics) and a reductionistic one in the other (agent-based). Generally, the two types of models are created and run independently and results from each are considered separately in decision-making processes.

This project integrated the two model types in a single decision-making architecture. The systems dynamics model captured and expressed the physical and engineered system. The ABM expressed human activity, i.e. decisions made about the target physical and engineered system; it also allowed the agents to respond to changes in the physical and engineered systems that resulted from their decisions.

Integrating engineering and science

The architecture of this project is conceptualized as the integration of engineering research activities with a scientific methods study. The primary engineering project focused on the engine which integrates the systems dynamics model of the target physical systems and the agent-based decision-making model. In order to test that engine, we built a functional user interface. This interface is

¹ <http://www.systemdynamics.org/DL-IntroSysDyn/start.htm>

² Eric Bonabeau. 2002. Agent-based modeling: Methods and techniques for simulating human systems. PNAS May 14, 2002 vol. 99 suppl. 3 P.1

³ Ibid.

accessed cognitively, i.e. through slider bars, radio knobs and other similar means. Output is presented in graphic or textual form. Concurrently, we worked with Intel Corp. to build an immersive serious gaming interface directed at these types of problems in which the user accessed the underlying engine experientially, i.e. through a serious game.

While those tasks were in progress, others on the project researched and then extended methods of stakeholder engagement in computational model development and use, exploring in depth the literature on participatory modeling and moving as necessary into other fields such as gaming and the literature on learning. In participatory modeling, the users play an integral part of the spiral development process. They provide input on the rules which drive their own behavior or their own understandings of the cause-effect relationships among phenomena. They then vet the resulting computational representations of these relationships and rules.

All three aspects of this project – the development of the interface between systems dynamics and ABM approaches, the development of a cognitive interface, and work with an immersive game environment – were instantiated through a participatory modeling approach to water resource allocation activity in the Middle Rio Grande in New Mexico. The interaction among these activities is illustrated in **Error!**

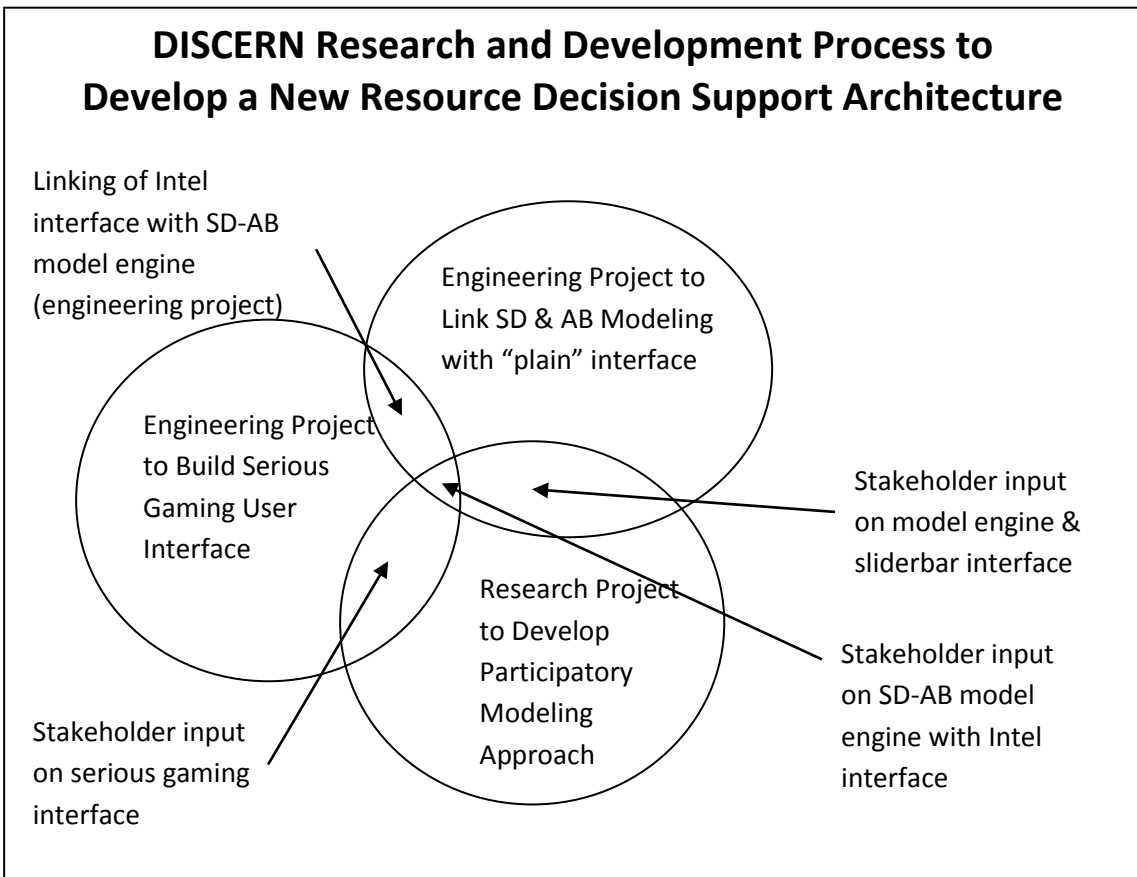


Figure 1: Interaction between engineering tasks and research project

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The Case Study – the Middle Rio Grande Basin

The example problem utilized to develop the modeling and process architecture is a water allocation problem: specifically, we targeted water resource management in the Middle Rio Grande Basin in New Mexico. This case was chosen because it exemplifies the challenges of resource decision making in a complex natural and human system where there is limited and nonintegrated data.

The Rio Grande Basin is located in a semi-arid region that has seen significant growth in population and per capita water consumption over the last several decades and ongoing drought conditions that have, strained available water supplies.⁴ The basin is the most populated region of the state and includes the City of Albuquerque as well as several smaller municipal water users. There is a sizable farming population with significant political influence at both the state and local levels. There are also six sovereign American Indian tribes in the Basin, including the Pueblos of Cochiti, Kewa (Santo Domingo), San Felipe, Santa Ana, Sandia, and Isleta. Each has unique legal claims to and jurisdiction over water in the Basin. The laws that govern water allocation in the Basin reflect the rich and complex history of multiculturalism in the region. These laws are an amalgam of customary practices developed through Pueblo water use since time immemorial, customary practices and law developed under Spanish and Mexican rule, U.S. treaty and federal law, tribal water codes, and state law. The rights of each Pueblo, which pertain to a certain amount of water to manage within its sovereign political boundaries, is protected under federal law. Water rights associated with federal lands (such as those managed by the Bureau of Land Management and Forest Service) and water projects administered by federal entities (such as the Bureau of Reclamation and Army Corps of Engineers) are also subject to federal law. All other water rights in the Basin are subject to the state law of prior

appropriation, which governs the allocation of water among users based on the principle of “first in time, first in right.” Water management in the Basin is further complicated by the overlay of the Middle Rio Grande Conservancy District, which holds significant water rights and authority over a 120 mile stretch of the river in the Basin.

In the State of New Mexico, water rights are treated as a form of real property under the law. Each water user holds a legal right to use a certain amount of water, which is defined by the historical origin, quantity, place of diversion, and uses of that right. A right is owned and in many cases may be transferred like other forms of property. However, the water rights of users in the Middle Rio Grande Basin have never been fully adjudicated. As a result, it is not clear who is entitled to what rights under the law and there is no firm correspondence between the “paper rights” claimed by users and the actual amount of “wet water” in the system. Finally, there are also exogenous claims on the Basin from compacts regarding the delivery of water in the Rio Grande to other states (Texas) and other countries (Mexico), demands made on the river by other basins within New Mexico, environmental laws, and restrictions and covenants that constrain water uses.

⁴ Middle Rio Grande Water Assembly, 2004. Middle Rio Grande Regional Water Plan 2000-2050: Volume I. Available at <http://www.waterassembly.org/5theplan.html>.

Ultimately, the allocation of water throughout the Middle Rio Grande Basin is subject to the Rio Grande Compact, which is a tri-state agreement signed in 1938 between the states of Colorado, New Mexico and Texas on how the Rio Grande waters are shared each year.⁵ Specifically, the compact stipulates Colorado's required delivery to New Mexico each year based on stream flow as measured at the Lobatos gauge near the state line. New Mexico is then required to deliver a variable quantity of the water to Texas based on flows at the Otowi Gauge. The compact also addresses a system of debits and credits allowing for water storage in basin reservoirs.

There are multiple types of demands on the water resources of the Middle Rio Grande basin which have the potential to develop adversarial behavior. *Urban demands* for water resources in the Middle Rio Grande Basin stem from the needs of the primary player which is the City of Albuquerque and multiple smaller communities such as Belen, Bernalillo, Espanola, Los Lunas, Rio Rancho and Socorro. Most urban demands are met through the pumping of a deep alluvial aquifer, which is hydrologically connected to the Rio Grande. Extraction of water from the aquifer can have effects on surface water flows in the overlying river. In December of 2008, the City of Albuquerque began utilizing surface water for the first time to meet a portion of the city's drinking water needs. The City acquired the water rights to divert this water from the Rio Grande through its investment in the San Juan Chama Project, which is a federally managed water project that diverts water from the Colorado River Basin into the Rio Grande. *Irrigated agriculture* is one of the largest demands on the water supply in the Basin. This includes commercial and small-scale irrigators and substantial rights held by each of the six Pueblos that are utilized for irrigation. Water for irrigation is largely taken from the Rio Grande and associated tributaries and distributed to crops by means of flood irrigation. *Environmental demands* for water in the Basin include water which is needed to maintain the integrity of existing ecosystems. The presence of the endangered fish species known as the silvery minnow (*Hybognathus amarus*) has led to the adoption of minimum flow requirements throughout the MRG, placing further demands on the water supply.⁶

The Rio Grande compact requires the basin to balance these diverse demands with variable supply over the long term. There are many ways of accomplishing this, such as limiting growth, improving conservation, effecting interbasin transfers, and the like. Different allocation strategies and the policies used to achieve them will have different implications for the environment, economy, and traditional water use practices.

This situation of competing interests and solutions stimulated several recent efforts to more thoughtfully craft long-term solutions. Such efforts have been spearheaded by the Middle Rio Grande Water Assembly, a broad-based stakeholder group that works in concert with other relevant organizations and the New Mexico Office of the State Engineer (the primary agency concerned with water allocation in the state). Together these groups developed a fifty-year water plan that was accepted by 19 local governments in the region and by the New Mexico Interstate Stream Commission and Office of the State Engineer.⁴ It took the Water Assembly and others roughly 3 years to reconcile

⁵ Office of the State Engineer, Rio Grande Compact, http://www.ose.state.nm.us/isc_rio_grande_compact.html

⁶ U.S. Fish and Wildlife Service, 2009. Endangered and Threatened Wildlife and Plants; Recovery Plan for the Rio Grande Silvery Minnow (*Hybognathus amarus*), Federal Register 74 FR 16232 16233

the competing agendas of the affected stakeholders. This was accomplished primarily through iterative face-to-face meetings and negotiations, supported by *ad hoc* access to data about the natural system through a variety of vehicles, including computational models.

Here we believe we can improve on the traditional practices of the past. ***Our working hypothesis is that stakeholders in the Middle Rio Grande Basin could produce a broader set of potentially acceptable and feasible solutions (i.e. policies) for shaping the future of the Basin with a more complete understanding of both the natural system and the associated socio-cultural and political systems. We posit that this “better understanding” will be most effectively achieved through engagement with tools that can present data and information related to the linkages between water, development, social/environmental/cultural values, and the operation of existing institutions.***

The decision support architecture developed through this project was piloted in the Middle Rio Grande Basin to examine how these tools might be utilized to promote enhanced understanding and decision-making in the context of complex water resource management issues. Potential applications of this architecture and its capacity to lead to enhanced understanding and decision-making was assessed through qualitative interviews with study participants who represented key stakeholders in the Basin.

Approach

Our approach assumed that decisions about the allocation of complex resources such as water use in the Middle Rio Grande Basin require simultaneous consideration of physical (environmental/natural) complexity AND social/political complexity of the systems involved. The optimal decision lies at the intersection of these two systems, as illustrated in **Error! Reference source not found..**

We further assumed that these two systems are qualitatively different and may require different decision support tools to navigate and understand. However, a decision-maker must understand the convergence between these two systems. Our project explores the possibilities of developing a process and tools for understanding this convergence between the social and natural systems that allows user(s) to access an integrated system through a user friendly interface.

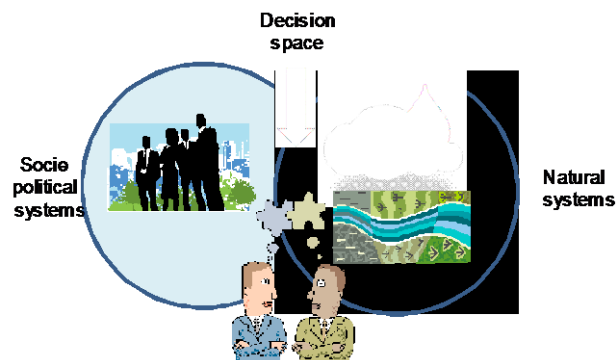


Figure 2: The decision space

Collecting and systematizing data about the structure and function of physical and biological systems draws upon the tools, traditions and methods of the physical and life sciences. Phenomena are (theoretically) observable and quantifiable. This type of information also is generally amenable to the taxonomies and structures used to construct databases, making it relatively easy to store and retrieve. Computational models can be validated through experiments. Analytic methods are rational, and decisions often revolve around optimization of some resource or ecosystem function. An oft-neglected challenge with this type of information is the development of a user interface that makes the system structure and function accessible and understandable to lay audiences, and amenable to the type of manipulation resource allocation decisions require.

Collecting and systematizing data about the structure and function of socio-cultural and political systems, on the other hand, deals with phenomena that are difficult to observe and quantify such as attitudes and values. In many decision processes, data about these phenomena are not methodically collected. Values and attitudes of participants are discovered through the negotiation and deliberation process and may often be misunderstood or poorly communicated. While it can be argued that politics takes place in the grey spaces between words, these grey spaces also significantly increase the risk of misunderstandings. This risk is magnified when decision processes are lengthy and involve groups with significantly different value structures and conceptual vocabularies, both of which are present in complex resource allocation decisions. Such is particularly the case in the Middle Rio Grande Basin where there multiple different cultural communities with different relationships with and claims on water.

This project does not argue that computational models can or should replace direct human interaction and negotiation in these types of complex resource allocation decisions. The challenge is to find the optimal balance between formalization of the socio-political sphere in computational models that support decision making and the creation of forums for the grey spaces to play out. The approach of this project is to explore the potential of combining these processes through the development of computer-based models of the human and natural world and various user interfaces to explore their interaction.

Computational Modeling

The computational modeling framework combines a system dynamics model of the physical/engineered system with an agent-based model of the human system. Specifically, an agent-based model was developed and combined with an existing system dynamics model of the Rio Grande Basin. The system dynamic model, known as the Upper Rio Grande Simulation Model (URGSiM), is a water planning and management model that captures agricultural and municipal demands, climate variable supply, and limitations imposed by regulation and policy. The Sandia EMPaSE Modeling and Simulation Environment was used to integrate the SD model with the ABM. EMPaSE is a hybrid modeling environment designed specifically for combining SD, agent-based, discrete event and sequential-modular modeling paradigms within a single model. Additional detail on each simulation component is provided below.

Incorporating the socio-political system

Stakeholders were engaged in the Middle Rio Grande Basin using a participatory modeling process to understand the key decision-making factors of different stakeholder groups. These factors were used to create rules for the ABMs and serve as a rough proxy for the different systems of values and attitudes at play in the pilot study. We used this knowledge of decision-making rules to create computational agents which could play the role of players of key stakeholders, with or without human players. Watching the computational agents make decisions that changed the hydro-environmental base provided one type of knowledge; engaging as a human player in the game with the computational agents provided yet another kind of knowledge.

Companion modeling, a form of participatory modeling, is a model development technique in which stakeholders actively participate in the development of a computational agent-based system. The approach was developed by the International Rice Institute for ecological work in Southeast Asia.⁷ It has since been used in Morocco⁸, Senegal,⁹ Asia,¹⁰ and elsewhere. The process uses role-playing activities to help elicit stakeholder preferences in key decision-making contexts, to make explicit their strategic goals, and to illuminate their political positioning.¹¹ The knowledge gained from these activities is captured and re-presented in a computational simulation of the local situation.

The purpose of the role-playing activities is “to create a shared representation of their [the stakeholders’] livelihood system based on their knowledge of the local context, and more generally, to capture the system of representation shared by all members in the community.”¹² Stakeholders may play the roles of themselves, or in some iterations, take on the roles of others.¹³

Users of this type of participatory process claim that it is highly educational for the participants, providing them with knowledge and insights into other players’ agendas that they would not otherwise

⁷ Naivinit, W., C.Le Page, G. Trébuil and N. Gajaseni. 2010. Participatory agent-based modeling and simulation of rice production and labor migrations in Northeast Thailand. *Environmental Modelling and Software*. Vol.25, no.11. Nov. 2010.; Castella, Jean-Christophe, Tran Ngoc Trung, and Stanislas Boisseau. 2005. Participatory Simulation of Land-Use Changes in the Northern Mountains of Vietnam: the Combined Use of an Agent-Based Model, a Role-Playing Game, and a Geographic Information System. *Ecology and Society*. Vol.10, No. 1.; Barnaud, Cécile, Panomsak Promburom, Tayan Raj Gurung, Christophe Le Page, and Guy Trébuil. 2006. Communication presented at the International Symposium Towards Sustainable Livelihoods and Ecosystems in Mountainous Regions, Chiang Mai, Thailand, 7-9 March 2006. <http://cormas.cirad.fr/pdf/barnaud2006.pdf>

⁸ Dionnet, Mathieu, Marcel Kuper, Ali Hammani, and Patrice Garin. 2008. Combining role-playing games and policy simulation exercises: An experience with Moroccan smallholder farmers. *Simulation Gaming Online First*. 19 Feb.2008.

⁹ Patrick D’Aquino, Christophe Le Page, Francois Bousquet and Alassane Bah. 2003. Using Self-Designed Role-Playing Games and a Multi-Agent System to Empower a Local Decision-Making Process for Land use Management; The SelfCormas Experiment in Senegal. *Journal of Artificial Societies and Social Simulation*. Vol.6, no.3

¹⁰ Gurung, Tayan Raj, Francois Bousquet and Guy Trebuil. 2006. Companion Modeling, Conflict Resolution, and Institution Building: Sharing Irrigation Water in the Lingmuteychu Watershed, Bhutan. *Ecology and Society*. Vol. 11. No. 2.

¹¹ Mayer, Igor and Martin de Jong. 2004. Combining GDSS and Gaming for Decision Support. *Group Decision and Negotiation*. Vol. 13. Pp.223-241.

¹² Gurung et al, op.cit.

¹³ ibid.

have.¹⁴ This benefit is particularly emphasized by those who take on roles other than their own during the course of the game.¹⁵ The game also produces knowledge about how players move through a particular complex system.¹⁶ Practitioner/facilitators have also found that development and participation in the game can help overcome a lack of trust between researcher and analyst that impedes the gathering of data that is used to construct the rules that define the roles in agent-based models.¹⁷ This is significant because capturing data on values and attitudes is methodologically difficult. They are generally implicit and have a high affective content which means that a trust relationship of some sort must be established between data collector and informant. Given the highly emotional agendas that are often present in scarce resource allocation processes, the development of this type of trust could be critical to the success of a modeling project.

All that said, we found that the processes defined in the literature on companion/participatory modeling constructed the games based largely on secondary source research and interviews with local participants. The published works on this topic are unclear as to method. They provided no information as to what they asked in the interviews (no sample protocols or descriptions of questions), what data they collected during the observations of the role plays nor how they collected that data. We believe this work makes a significant contribution to the literature on the participatory modeling process through our explicit description of our processes throughout the modeling project and our documentation of our methods of data collection from stakeholders.

Method

The final deliverables of this project included two key components: 1) a simulation environment that combined system dynamics models with agent-based models based on stakeholder rules of behavior, and 2) a process for capturing relevant information about stakeholder behavior and utilizing it to construct agent-based models of stakeholders. As the deliverables were constructed, we gained knowledge regarding the effectiveness of different types of user interfaces and potential applications of these processes and tools.

This section provides a discussion of the steps used to construct the deliverables. The methods used for constructing this integrated architecture follow the spiral or iterative development path often used in software development. The section following (Results) describes the result of the application of our method – the data we collected and the models we constructed.

Ideally, our companion modeling approach would have followed these seven steps. In this section, we discuss a method for each. In the next section, we discuss the results of our application of each.

¹⁴ Dionnet et al, op.cit.

¹⁵ Gurung et al., op. cit.

¹⁶ Ibid.

¹⁷ Castella, Jean-Christophe, Tran Ngoc Trung, and Stanislas Boissau. 2005. Participatory Simulation of Land-Use Changes in the Northern Mountains of Vietnam: the Combined Use of an Agent-Based Model, a Role-Playing Game, and a Geographic Information System. 2005. *Ecology and Society*. Vol. 10., No. 1 3

1. Identify all stakeholders relevant to this project. These will become the ‘agent classes’ in the computational social model.
2. Develop and implement a nominal social model structure and key variables using subject matter experts (SMEs). This also will allow us to assign nominal values to those variables
3. Develop (acquire access to) a model of resources and other relevant domains.
4. Develop and integrated agent-systems dynamics model.
5. Develop the interface for the user with the model complex.
 - a. Develop a standard interface
 - b. Develop a game-based interface
6. Get ‘social validity’ for the model structure and the values for key variables through engagement of stakeholders with the model through each of the two interfaces. Re-calibrate the model
7. Repeat step 6 as necessary to gain consensus of stakeholders on model structure and the dynamics of the simulation.

Step One: Identify stakeholders

The first step in this type of modeling is to identify the relevant stakeholder groups and the types of decisions they may make. One of the primary reasons participatory processes fail, or do not come to an agreement all stakeholders can accept, is that key stakeholders are excluded from the process, or invited into it late. Often these exclusions are unintentional, but the results are as damaging to the process as if they were deliberate.^{18,19}

To avoid this problem, we used a tool developed by Glicken called a stakeholder map.²⁰ This tool creates a conceptual social map of the problem space. It generally is created to a first order by project personnel, and then tested for social validity with participants in that social space. A full test for social validity requires the map to be vetted by participants throughout the space to overcome observer/participant bias.

The stakeholder map forces a project manager to be explicit about his/her understanding of the relevant social space. This map, and the explicit understanding it creates, can then be used as a decision aid to delineate the social space particularly relevant to the project. It generally is a space smaller than the total problem space. If particular groups are excluded from the process, they are excluded deliberately rather than inadvertently. While this cannot eliminate problems due to non-participation by certain groups, it both reduces their inadvertent occurrence and when decisions to omit a group are challenged, the project manager is prepared to counter them.

¹⁸ Glicken, J. 1999. Effective Public Involvement in Public Decisions. *Science Communication*, Vol. 20, No. 3, 298-327

¹⁹ Finney, C. and R.E. Folk. Developing stakeholder understanding, technical capability, and responsibility: The New Bedford Harbor Superfund Forum. *Environmental Impact Assessment Review*. Volume 15, Issue 6, November 1995, Pages 517-541

²⁰ Glicken, op. cit. Jessica Glicken (now Jessica Glicken Turnley) is a participant on this project.

The types of decisions each stakeholder (or stakeholder class) will make are different also. In the agent-based model developed for this project, water basin stakeholders are the agents and their decisions and cues are the rules. Each stakeholder group makes different kinds of decisions related to water. The decisions they make are based on cues in their environment. In the case of a farmer for example, water-related decisions might depend upon such cues as the available water supply, the amount of water required by particular crops, income, labor conditions, and the like. Each class of stakeholders weights these cues differently based on cultural values and attitudes. For example, given the same cues, farmers who grow crops for large-scale commercial production may make different kinds of decisions than small producers who grow organic vegetables for farmers' markets or those who grow traditional crops to maintain their cultural heritage. These decisions will have different kinds of consequences for the physical system.

Through iterative rounds of discussions with stakeholders and area experts, we identified several key stakeholders to model as agents. The two stakeholder types chosen for modeling in this study were agricultural and municipal water users because of the significant impacts their decisions have on the physical/hydrological system. Once identified, stakeholders representing each type of agent were recruited to participate in the modeling process.

Step Two: Develop and implement a nominal model structure and key variables.

For this project, this knowledge was gained by the team through interaction with groups such as the Middle Rio Grande Water Assembly, the New Mexico Water Dialogue, and others, and through review of relevant literature on water allocation in the Middle Rio Grande Basin and other related issues. We utilized the subject matter experts on our team to engage with these stakeholders and do the research.

The stakeholders who agreed to participate in this project had two primary functions. In one, they helped validate decision rules developed by our subject matter experts. They did this through data capture sessions. In the other, they helped develop a serious gaming interface that would overlay the models driven by the decision rules. As a consequence of their participation in both these types of sessions, we also learned their preferences for different types of interfaces and engagement styles with the model for different types of decisions.

In data capture sessions each stakeholder was asked to work through three different environmental scenarios in which cues prompting water management decisions were presented to the participants. The cues were presented through a computer interface composed of numeric and graphically displayed information. Decisions were made by manipulating slider bars and radio buttons on the interface. Each scenario presented the stakeholder with a series of data simulating different hydrological and economic conditions.

Farmers were presented with an interface with numeric cues regarding the water supply, their income, and work hours and asked to make decisions regarding the sale and lease of water rights and the number of hours they were willing to allocate to farm-related work. Stakeholders representing municipal water utilities were presented with an interface with graphical and numeric cues representing

the water supply and various options for meeting municipal demands. Each scenario contained 10 rounds, each representing a different time step equivalent to one year in the physical system. After making and submitting decisions in one round, the participant was presented with a new set of values for the cues that accounted for the decisions made in the previous round.

The decisions made in each round for each of the three scenarios was automatically captured and stored on the hard drive of the computer. Modelers then combined the data and performed multiple regression analysis to generate (computational) agent models representing the two stakeholder types. In each agent model the dependent variables are agent decisions and the independent variables are the cues and underlying environmental factors that prompt those decisions. When combined, the agent models respond to the environmental variables generated by the system dynamic model. The system dynamic model in turn responds to the decision variables generated by the agent models. The combined simulation thus combines models of both complex physical/natural phenomena and complex social processes into one single model.

The agent based model was developed using the Cognitive Foundry, a collection of Java software tools for intelligent agent modeling [J. Basilico, K. Dixon and Z. Benz, The Cognitive Foundry, SAND2008-5413A]. The agent-based model incorporates both our model of how decision makers interact with each other and with water resources, as described by the project SMEs, and methods for creating software agents that represent human decision-makers. Note that the first of these determines both how human stakeholders interact with the simulation, by determining what cues they will see and what choices they are allowed to make, and the input-output structure of the software agents.

In the most general terms, a model of a stakeholder, or group of similar stakeholders, is any model that takes the input cues and returns decision outputs appropriate for those input cues. The agent software is written in such a way to make it possible for many types of models to be used for this input-output mapping; some early tests were done with simple models that used either hard-coded outputs or purely random outputs. However, the goal was to create agent models that 1) reflected actual stakeholder decisions and 2) captured the stochastic nature of those decisions. To accomplish this, models based on simulation log files were created using Bayesian Linear Regression.

In standard regression, we assume that there is some function that maps input variables to output variables, and use any of several of techniques to approximate that function given samples of input-output pairs. The Bayesian approach to this works with distributions of values. For a set of input-output pairs, Bayesian regression produces a multivariate Gaussian representing the relationships between input vectors and observed outputs. For a specific input vector, e.g. for one round of cues in our simulation, this can be used to produce a predictive distribution of output values for that input vector. A single sample from the appropriate predictive distribution is treated as an agent's output on that round. Note that different agents given the same input vector, or the same agent given the same cues in different rounds, will choose a different sample from the same distribution. If that distribution is very narrow, as when there are adequate data to indicate that the modeled player(s) always chose the same output given those inputs, the agents' outputs will be similar. If the distribution is very broad, the agents' outputs will be very different. The latter case reflects the situations in which decision makers choices vary even when they are presented with the same information.

This procedure is actually applied independently to each decision made by each stakeholder. The full model of a farmer or municipality therefore consists of several multivariate Gaussians, one for each

output. Constraints between outputs, such as the requirement that the water rights a farmer uses for irrigation plus those he sells plus those he leases out must sum to the total water rights he owns, are applied after the predictive distributions are sampled on a given round. This is very similar to the way the user interface forces a player to meet this constraint; a farmer may try to sell more water rights than he has, for example, but the interface caps the actual value.

There are a number of choices possible in choosing what data to use to construct these models. We can combine all the farmer log files in order to create a model of an ‘average’ farmer, we can use each individual farmer’s logs to create models of individuals, or we can try to group farmer logs in a way that captures particular subtypes. For the latter, we relied on a combination of automatic clustering of the data (a machine learning technique) and analysis of the qualitative data.

Step Three: Develop (acquire access to) a model of resources and other relevant domains.

Project participants had been involved in the development of URGSiM, the system dynamics water planning and management model that captures agricultural and municipal demands, climate variable supply, and limitations imposed by regulation and policy in the Middle Rio Grande Basin. For purposes of this project we make use of this existing model.

Step Four: Develop an integrated agent-systems dynamics model

The central challenge in coupling models developed in different modeling paradigms is managing the transfer of data among the various constituent models. The key observation that allows the models to interact effectively is how data flows within each constituent model: using either a “pull” or “push” model.

System dynamics models invariably use a “pull” data transfer model. Each step in a causal loop relies solely on data computed in a previous step. When evaluating a step, the simulator will read (pull) the required data in from the referenced variables, perform the computation specified by the step, and store the result back to a variable so that it is available to subsequent steps. The key property of pull-based data transfers is that it is the consumer of the data that initiates the data transfer. In contrast, event-driven simulation paradigms – including agent-based simulations – rely on data transfers (communication patterns) that are initiated by the data producer. For example, one agent will prepare a message and send (push) it to the intended recipient agent, oftentimes triggering a response from the recipient. Similarly, in a discrete event paradigm, the main event queue will iteratively push the next event in the queue to the designated target, triggering the corresponding event processing function.

Push-based communication paradigms may be emulated using pull-based patterns by having the recipients continuously poll their data sources. However, this approach places a significant burden on the individual recipients and can complicate the verification process for both the environment and the model. Instead, we developed the integrated agent-based / System Dynamics model within the Extensible Multi-Paradigm Simulation Environment (EMPaSE). EMPaSE implements two parallel communication systems: a pull-based system (ports) for general computation, and a push-based system (plugs) for messages and events.

Providing explicit systems for both pull and push patterns allows EMPaSE to natively support both general procedural-based and event-based simulations. Further, the hierarchical organization of modules within an EMPaSE model allows modelers to scope portions of a model and define independent execution drivers. This enables separating conditional components, loops, and event or message handlers from the main execution driver. Through the use of push and pull communication and execution scoping, EMPaSE allows modelers to seamlessly integrate sequential modular, systems dynamics, discrete event and agent-based modeling paradigms within a single multi-paradigm modeling and simulation environment.

Step Five: Develop the interface for the user with the model complex.

Two different kinds of user interfaces were developed to examine potential applications and usability of the combined model engine. The first is an adaptation of the interface used to capture data for the agent modeling. In this interface information is displayed in a textual format or in graphs of various types and outputs are manipulated through slider bars and radio buttons. The second interface was developed in partnership with Intel Corporation. This interface is game-based and is designed to stimulate a high level of engagement of the stakeholders in the movement and development of the simulation. Developed using video game software, the interface presents a fully immersive environment in which the player sees farms, crops, and building construction and can see changes to the built and natural environment based on his and others' decisions. Through the iterative process of participatory modeling, participants were asked to evaluate the applications and merits of these interfaces and the underlying model for use in various resource decision making and education processes.

For development of the serious game-based interface, Sandia teamed up with Intel Corporation. Intel was developing an open source gaming environment and was looking for a test case. Intel was creating the ScienceSim game engine²¹ as a development platform, and had many questions about the configuration of the interface it wanted to put to actual players in the water arena. The partnership between this project and Intel was a good fit. This project involved developing the underlying model that would incorporate the rules and relationships of the game. Intel was interested in developing an interface that would allow stakeholders to engage with the model.

We explored the benefits a serious game interface would provide to this process versus the much less expensive and less time-consuming standard interface of radio knobs and sliders. We explored the nature of games, of serious games, and the ways in which these types of exercises can (not) influence the outcome of processes such as those targeted here: the allocation and use of water in the Middle Rio Grande Basin. This raised interesting and important questions about learning and about the role of computationally based tools in decisions and learning.

Games, serious game, sandboxes and other means of engagement

Approaching learning from the study of play or the use of digital devices which themselves create play through games has led to two significantly different approaches to the use of digital media in learning

²¹ Intel Corporation, 2011. ScienceSim. <http://sciencesim.com/scisim/index.php?page=home&btn=1>

through games. In one, the focus is on digital media and on the game itself. In the other, the attention is on the interaction between the digital media and the learner. These differences correspond roughly to the two different types of interfaces or engagement mechanisms we developed for our model, and represent fundamentally different approaches to learning and the corresponding role digital technology plays in the learning process. We give a brief overview here, and go into much greater detail in Appendix A.

In the first approach, the game becomes an artifact. The game takes on a role similar to an engaging lecturer. The focus is on making the lecturer (the digital game) as effective as possible in the transmission of knowledge. This derives from a cognitivist tradition of learning that assigns a relatively passive role to the learner. If the information is (packaged) and transmitted effectively, the learner will learn. There is a central role for serious games in this approach.

Countering this approach are those who focus on the learning process itself, on the way in which the learner engages with the material, including the transmission medium. In this tradition of game-based learning and digital game-based learning the focus is the learning process itself. This lends itself well to what is called a constructivist approach to learning. The primary assumptions of constructivism are that the learner is the active agent, content is relative, every learner has a unique understanding of it, and thus a unique learning experience. Situated cognition, in which the *knowing* is seen as inseparable from the *doing* is a form of constructivism in which learning is measured through effective application in the real world rather than the abstract accumulation of *knowledge*, as what is *known* depends on the situation, the agents present, and the context.

In brief, we associate the *serious game* approach primarily with cognitivism and the game based learning approaches with constructivism. Participatory modeling as a model-building methodology would fall into the constructivist, situated cognition camp. For both a serious game and participatory modeling, the role of the digital medium is to act not as an artifactual interface but as an integral and active player in the learning environment. Not only do the 'students' or learners benefit from the interaction with the digital media, the computational 'game' is revised based on the learners' interaction with it. The learning thus goes both directions. This contrasts with the use of a standard interface with radio buttons and slider dials. In this case, the presentation of information through text or graphs suggest a cognitive approach. The goal is not to engage the learner but to convey information. The two screen shots in **Error! Reference source not found.** illustrate the different methods of engagement. The screen on the left is a standard interface which cognitively engages the user. The screen on the right is a game interface which engages the user experientially.

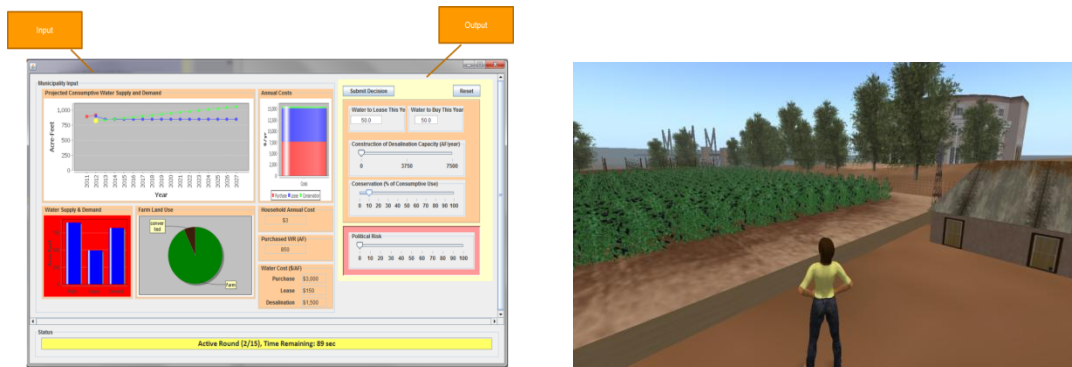


Figure 3: A standard and a gaming interface

This project developed both a standard interface and a serious game approach. We combined a participatory approach to the overall model building with parallel exercises using the two different modeling interfaces. As we said earlier, participants were asked to evaluate the applications and merits of these interfaces and the underlying model for use in various resource decision making and education processes.

Step Six: Get ‘social validity’ for the model structure and the values for key variables through engagement of stakeholders with the model through each of the two interfaces. Re-calibrate the model

The combined simulation was then ‘vetted’ with stakeholders. Castella et al. (2005) calls this last step ‘social validation.’²² Since ‘real people’ produce the rules of a model, these ‘real people’ understand the model and how it differs from the real world. Social validation legitimizes the model with stakeholders such that they are more likely to accept its output. The model/simulation can then be used to explore how particular decisions may play out.²³

Internal Review Board vetting and acceptance

Since we were collecting data from human subjects, the project was subject to review by Sandia’s Internal Review Board (IRB) to ensure that we met all requirements for the protection of human subjects. The project met Sandia’s requirements for an expedited review. Upon submission of required documents, we received approval to proceed.

Stakeholder sessions

An initial list of participants was identified by the project SMEs based on their knowledge of individuals who represented target stakeholder groups. Additional participants were identified through the process of snowball sampling, based on the suggestion of other participants. Recruitment was conducted by phone and email. Potential participants were initially contacted by phone. If the recruit agreed to participate, a follow-up email confirmed participation and provided the participant with the time, day, and location of the session. Each participant was contacted by phone or email the day before the

²² Castella et al, op.cit.

²³ Dionnet et al, op.cit.

session to ask if the participant had any questions or concerns and to provide a reminder about the session time and location. Recruitment scripts can be found in Appendix B.

We met with the stakeholders at a meeting room in a local restaurant in Albuquerque, a central location for stakeholders who were coming from throughout the Middle Rio Grande region. All meetings were attended by members of the project team. Participants were provided food during the meeting, but no other compensation.

Each session lasted approximately two hours. They all proceeded generally as follows:

- Oral introduction and background presentation by the project team,
- Questions and answers (Q&A),
- An overview with Q&A and signing of participant consent forms,
- Participant use of the computer model interface to gather quantitative data regarding participant decision making, and
- A facilitated discussion about the model and how it might be improved to more accurately reflect human decision making processes.

A detailed set of instructions for the stakeholder sessions is included as Appendix C.

The room was set up so each participant had his own computer. The game and standard interface were served to each participant through a web based connection.

Each meeting was audio recorded with permission from all participants. Members of the project team also took notes on the proceedings, allowing capture of non-verbal expressions and interactions.

Each meeting began with an introduction of participants, presentation of the project, its purpose, and its progress to date. The presentation was made by one of the project team. For the meetings involving the gaming interface, the game designer from Intel also made a short presentation on his portion of the project.

The meeting gauging the gaming interface was moderated by the interface designer from Intel. The programmer, who was located in England, listened to the proceedings via Skype.

The meetings involving the standard interface and the data capture meetings were moderated by project personnel.

We also collected data through feedback from the participants in both discussion and through questionnaires.

Results

Step Zero: Calibrating the Team

The team for this project was multi-disciplinary by design. It included computer scientists, resource economists, anthropologists, hydrologists, geologists, engineers, and a sociologist. Furthermore, team

members came from multiple institutions. Sandia National Laboratories had the project lead. Other team members came from universities and the private sector (small business).

The project team encountered many of the common difficulties faced by multi-disciplinary and multi-institutional teams as they work on common problems. Administrative issues regarding contracting, intellectual property and the like needed to be addressed. Conflicting (or at least dissimilar) institutional agendas pushed team members to advocate different directions for the project at times. This was compounded by the significant communication problems that needed to be addressed for multi-disciplinary work to become truly interdisciplinary. The well-recognized issues of jargon and specialized language came into play. At times, team members used similar vocabulary with significantly different meanings attached. Methods of parsing problems or even defining what is a problem vary from the social sciences to the physical and life sciences. Definitions of what constitutes data are different. Methods for collecting certain types of data may be unknown to some team members and assumed as part of the project plan by others.

The project team spent a considerable amount of time in the 'norming' and 'storming' phases of team formation. Participation as a group in a project management workshop provided the catalyst needed to coalesce the team around a commonly accepted problem. Although this phase was not included as part of the formal project plan, the amount of time and team energy it required suggest that it should have been.

Step One: Identifying stakeholders

As mentioned in the methods section, the exclusion or late inclusion of key stakeholder groups in any process is one of the primary causes of failure for these processes. To avoid this pitfall, we developed a stakeholder map as described by Glicken.²⁴

We used our subject matter experts to create our first order map. Our project experts are Elizabeth Richards, Vincent Tidwell and Suzanne Pierce (formerly with Sandia but now at the University of Texas). We then vetted the map through the New Mexico Water Assembly, the multi-stakeholder water basin group described in the case study section above. Members of the New Mexico Water Assembly who reviewed the map suggested relatively minor changes which we made. The map is shown in **Error! Reference source not found.**

From this map, we chose as our primary stakeholders of interest two sets of water rights owners. One we called the 'rural senior,' or farmers, the other the 'urban junior,' or municipalities. For our purposes, rural seniors included individuals water rights holders, acequias (irrigation ditch associations of Hispano origin), and the Pueblos. While there are important differences among these types of rural senior water rights owners, for our purposes they were similar in that they each owned surface water rights and used water for various agricultural and other purposes. Urban junior owners included municipalities (such as the cities of Albuquerque, Rio Rancho and others) and large industry like Kirtland Air Force Base (KAFB). Again, while there were difference among these users, they all acquired rights later than the rural

²⁴ Glicken, op.cit.

seniors, which is a critical point in a first-in-use system such as that in place in New Mexico. In most cases the urban juniors access their rights through groundwater pumping; however they are responsible

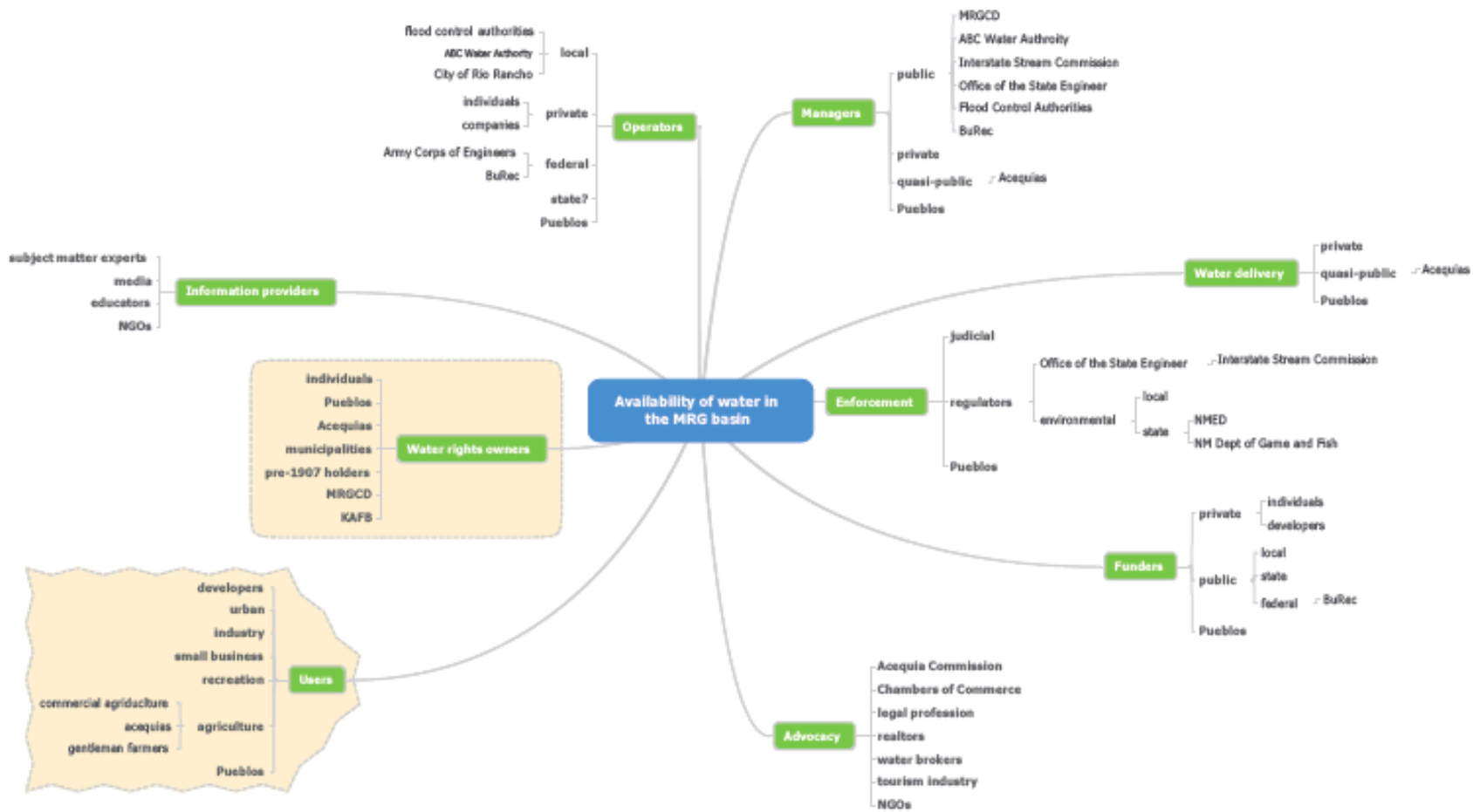


Figure 4: Stakeholder map. Shaded groups are those represented in the model.

for off-setting any impact they may have on the Rio Grande. Urban junior water rights holders used water for households, industrial use, small business use, recreation, and development.

Note that our initial model included only a very small subsection of all stakeholders involved in water issues in the Middle Rio Grande Basin (see **Error! Reference source not found.**). However, we believe we captured the majority of water rights holders and use functions with a high level of aggregation.

Step Two: Develop and implement a nominal social model structure and key agent decision-making variables

For purposes of our initial experiments, two sets of agents were developed: ‘rural seniors’ and ‘urban juniors’, often referred to for simplicity as ‘farmers’ and ‘municipalities’. Information for the initial structure of the model and the key decision-making variables for our agents came from the project SMEs. Decisions largely addressed behavior around utilization of water rights. Although the factors included in the model were largely economic in nature, the decisions that they represented involved deep social values. For instance, farming a particular piece of land may not make good economic sense; however, because of a farmer’s connection to the land and family tradition, cultivation will continue. Likewise, for a municipal agent, conservation may be the cheapest option for “new water supply”; however, perceived political risk might drive the agent to diversify the development portfolio.

Farmers

We assumed each farmer had water rights to a certain amount of water per year (100 AF). For the purposes of investigating potential conflict with other water rights holders and water users, the key decision farmers face is how to use their water rights. In our simulation, their choices were to use their water rights to irrigate their land, to lease their rights to others for a year, or to permanently sell their water rights. A farmer may mix these decisions: for example, he may choose to use half his water rights for irrigation, lease one quarter, and sell one quarter. In addition, the farmer has the option to lease in additional water rights in a drought year to make up for shortage in actual water delivered. Note that we do not allow other uses of water rights, and water rights must be used – our simulation actually enforces these constraints by ensuring that all water rights owned are designated for irrigation, sale, or lease. A related decision farmers may make is how much time they will spend working at a job other than farming. This is assumed to be related both to whether/how much they intend to irrigate, and how they will support themselves. The decisions each farmer could make for a given year are summarized in table 1.

We structured the farmers’ decisions largely as economic decisions, which determined many of the cues we hypothesized that farmers might use to make water use decisions. Expected water delivery is an example of a ‘global’ input, a cue determined by factors outside the farmer’s control. Additional cues of this type that we included are the prices to lease or sell water rights, the income a farmer could earn in off-farm work, and the cost of living. Many of these cues are simplifications of more complex factors. For example, our model has a single cue for the expected water delivered in a year, which in reality is a function of snowpack, weather predictions, other demands on the water supply, etc. To represent social factors that may also play a role in farmer’s decisions, we also supplied information about what neighboring farmers are doing. Specifically, we included a global cue showing the percentage of

neighboring farms that are still being used for farming. These global cues, or inputs, are listed in table 2.

Table 1. Farmer decisions

Farmer Yearly Decision ('output')	Range of allowable values
Water rights to use for irrigation	0 to 100 AF in total water rights owned (and not sold or leased)
Water rights to lease to others for a year	0 to 100 AF in total water rights owned (and not used or sold)
Water rights to sell permanently	0 to 100 AF in total water rights – WR used – WR leased
Water rights to lease from others for a year	0 to 100 AF in initial water rights owned
Hours per week to work off-farm	0 to 60 hours

Table 2. Farmer 'GLOBAL INPUT' Cues

Expected % water delivery
Market water sell price
Market water lease price
Annual living expenses
Hourly wage off-farm
% neighbors still farming

'Local' inputs or cues are those that depend on the farmer's previous decisions. In our simulation, these included water rights owned, and current bank balance.

Municipalities

Municipalities are also assumed to possess certain water rights, but in most scenarios these rights provide inadequate water to meet the growing demand within the municipality. The key decisions for the 'urban juniors' were therefore how to increase supply and/or reduce demand so that supply meets or exceeds demand. The options were to buy more water rights, lease water rights in a given year, or to implement conservation measures (which will reduce demand). The municipal agent also had the option to develop non-potable water supplies, assumed to be brackish groundwater in this case, which required the construction and operation of a desalination plant (requiring 5 years to construct).

These decisions are summarized in table 3. Note that the decision to construct a desalination plant can only be made once during a simulation.

Each of these decisions is assumed to carry some political risk. Ideally, the risk associated with each potential decision would be an input or cue, but there is little information available to quantify that risk. For our initial simulation, we asked stakeholders to assess the risk associated with their decisions, so that political risk was actually a decision output in this case.

Table 3 Municipality decisions

Municipality Yearly Decision (output)
Water rights to buy
Water rights to lease
Construct small or large desalination plant?
Impose conservation measures (0-100% of baseline)

The cues for the municipalities were quantities that either help them evaluate the expected supply and demand, or that help them evaluate the cost of a particular decision. These are summarized in table 4.

Table 4 Municipality cues

Current water rights
Projected future demand
Drought water shortage
Water Right Lease Price
Water Right Purchase Price
Desalination Plant Construction Cost Per AF
Conservation Cost Per AF

Simulation dynamics

Each game was composed of a sequence of 10 ‘rounds’, each of which corresponded to a year. Each participant played three games, each with a different sequence of climate and economic conditions. In each round, a set of inputs was presented to the player based on a scenario file that was selected by the game master before the game began. (Recall that we had two player or agent types: farmers and municipalities.) Each player selected from a set of possible decisions. Some portion of the input variables was modified by the chosen set of decision settings through the connection with the underlying resource model.

Each round was timed: this timing was configurable by the game master at the beginning of the game. At the end of the round, the configuration of the player’s output decision area was submitted as his decision output, although a player may submit his decision prior to the round timeout.

There were two types of input data: global and local. Global input data applied to all players of a type (e.g. all farmers or all municipalities). Examples of global input data were drought forecasts and water market prices. Local input data was unique to a player (not a player type) and was usually dependent on the decisions the player made. Examples of local input data included a player’s bank balance, the number of water rights he held, and expected farming input.

In this initial iteration of the game, individual players’ decisions had no effect on the decisions of others or on the input cues other players see. Also, in this standalone version of the simulation, information about water resources was provided from a static scenario file rather than from the system dynamics model.

Step Three: Develop (acquire access to) a model of resources and other relevant domains.

As mentioned in the Methods section, project personnel had participated in the development of and had access to URGSIM. This system dynamics model of the water resource planning in the middle Rio Grande Basin was used as the physical environment model for this project.

The model of the physical environment operates within a system dynamics framework employing the commercial software package Powersim Studio 2008.²⁵ Adoption of a system dynamics structure facilitates the integration of the physical/engineering system to the agent-based modeling, within a computational framework allowing experiments to be conducted in real time. The physical and engineering systems model is physically based, formulated according to a temporally dynamic water budget. Temporally the model operates on a monthly time step calibrated over the period of 1975 to 1999. The spatial extent of the MRG model extends from the Colorado border in the north to Elephant Butte Reservoir in the south. Between these reservoirs the Rio Grande is broken into seventeen interacting reaches as delineated by major stream gages (see Figure 5). Each reach is modeled with three interacting components representing the surface water, irrigation conveyance, and groundwater systems.

The surface water system tracks Rio Grande flows between Colorado and Elephant Butte Reservoir. A selected sequence of historic gauged flows is used to seed mainstem Rio Grande inflows (a variety of sequences are available addressing differing degrees of climate variability). Main stem flows are augmented in each reach by local inflows. Inflows to each river reach include gauged tributary inflows (based on historic gauged flows, correlated with the mainstem inflow sequence), irrigation conveyance return flows, and urban waste water return flows. Losses from the surface water system include evaporation from the river and reservoirs, irrigation conveyance diversions, and river losses to groundwater. Evaporative losses are calculated using a modified Penman Monteith equation²⁶ while accounting for variation in the open water surface area (as related to river discharge and reservoir storage). Meteorological data used to drive the evaporation calculation are taken from local monthly averaged weather station data that is correlated with the selected historic inflow sequenced used to seed the analysis.

The engineered irrigation conveyance system routes water through diversion ditches from each river reach to the agricultural fields and then back to the river. The irrigation conveyance system experiences losses to the groundwater system through canal seepage and crop seepage. Additionally, water is lost to crop evapotranspiration, again based on the modified Penman Monteith equation. Crop water

²⁵ See www.powersim.com

²⁶ Brower, A., 2004, "ET Toolbox, Evapotranspiration Toolbox for the Middle Rio Grande. A Water Resources Decision Support Tool" Water Resources Division Technical Service Center, Denver, Colorado, Bureau of Reclamation, United States Department of the Interior.

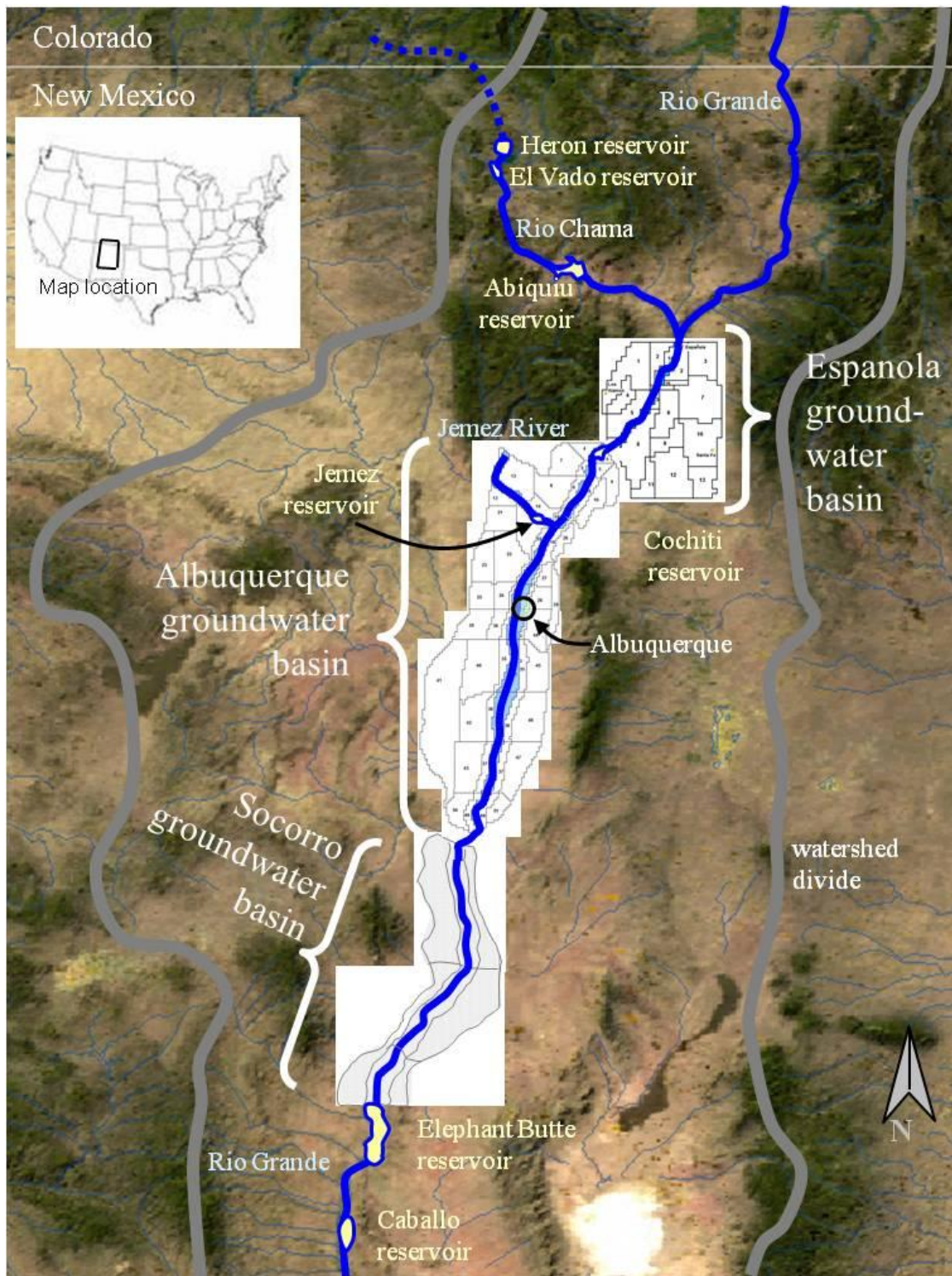


Figure 5: URGSiM spatial extent including locations of reservoirs and modeled groundwater basins.

consumption is based on the mix of crops and associated acreages in each reach as of 2002²⁷. Irrigation return flows are calculated as the difference between the initial diversion and the losses to groundwater and evapotranspiration.

The groundwater modeling component balances flows between the Rio Grande and the underlying aquifer system for each reach. Flows between the river and aquifer are driven by changes in river flow and the hydraulic head of the aquifer (i.e., river gains/losses occur as river flow and/or groundwater pumping vary). Groundwater inflows include mountain-front recharge, irrigation canal and crop seepage, and river losses. Groundwater withdrawals include riparian evapotranspiration (calculated in a similar manner to crop evapotranspiration) and groundwater pumping for agricultural and urban purposes. Urban areas have surface water rights to offset pumping impacts on the Rio Grande (e.g., river losses).

For those reaches with irrigated acreage, diversions based on time of year and demand are calculated and diverted off the main stem of the river with a return flow from the canal to the river and a through flow into the next reach.

Ultimately, surface and groundwater use in the basin is governed by State issued water rights. As part of this project, URGSiM has been adapted to manage water allocation according to water rights and associated priority dates. Although the Middle Rio Grande has yet to be adjudicated, the model allows the exploration of alternative futures as to how rights might be assigned relative to priority and how the rights will eventually be managed. Appendix D provides a detailed description of updates made to URGSiM.

Step Four: Develop an integrated agent-systems dynamics model

The ultimate goal of this project is to develop a simulation environment that integrates agent-based models of human decision-making with traditional system dynamics (SD) models of resource constraints and economics, supported with advanced processes and tools for expedited data capture. In this step we utilize data from prior stakeholder engagement to create synthetic agent models and integrate these models with a system dynamics model of Middle Rio Grande water resources.

Develop synthetic agent models

The July stakeholder sessions provided gameplay data by which we were able to construct synthetic farmer and municipality agents. Developing synthetic agents serves multiple purposes: 1) the initial data analysis helps to understand strategies used by decision-makers and whether/how much they vary, and 2) software agents behaving 'like people' enable us to run an integrated simulation with a sufficient

²⁷ United States Army Corps of Engineers (USACE), United States Geological Survey (USGS), United States Bureau of Reclamation (BoR), United States Fish and Wildlife Service (USFWS), United States Bureau of Indian Affairs (BIA), United States Army Corps of Engineers (USACE), United States Geological Survey (USGS), United States Bureau of Reclamation (BoR), United States Fish and Wildlife Service (USFWS), United States Bureau of Indian Affairs (BIA), and the International Boundary and Water Commission (IBWC), 2002. "Upper Rio Grande Water Operations Model" Model Documentation, Draft by the Technical Review Committee. <http://www.spa.usace.army.mil/urgwom/docintro.asp>

number of individual decision-makers that the effects of their decisions on the physical system dynamics model were noticeable.

During the July meetings we had 19 stakeholders playing 3 scenarios each – a Limited Drought, an Increasing Drought, and a Cyclic Drought scenario. However, on examining the log files we found that some of them were incomplete, and some had errors. For example, one stakeholder reported that he entered a value much larger than he intended, which threw off the values for the rest of the game. After eliminating these logs, we had 35 farmer log files (12 for the Limited Drought scenario, 13 for the Increasing Drought scenario, and 10 for the Cyclic Drought scenario) and 18 municipal log files (7 for the Limited Drought scenario, 6 for the Increasing Drought scenario, and 5 for the Cyclic Drought scenario). In the remaining logs, we looked for patterns in the data and correlations between input values and output decisions.

Out of all the input data presented to farmers, the most significant cues (based on correlation with output decisions) were: bank balance, water rights, water sell price, water lease price, and expected water delivery. Therefore, these were the input values used in the regression for each of the farmer decisions. Note, however, that the questionnaires completed by the participants indicated that many factors and decisions that farmers felt were important were not included in our interface, and that some we included were irrelevant. For this reason, even ‘significant’ inputs often did not show obvious relationships to output decisions, as for example in Figure 6 showing the amount of water rights farmers leased to others versus the lease price.



Figure 6: Water rights leased (Acre feet of water) by farmers versus the sell price (in \$).

Note again that although a linear regression can be fit to the data (Figure 7), Bayesian regression produces a distribution from which agent output ‘decisions’ are sampled, so there will be a similar stochasticity in agents’ decisions as that seen in the actual logged data. This will be reflected both in differences between different agents using the same underlying model, and differences between simulations.

We assume that most of the municipal decisions are based on a normalized supply-minus-demand (Figure 7). Supply in this case is represented by the water rights the city owns; demand by population times per capita use, taking into account current conservation measures. We further assume (based on input from the SMEs) that the municipal agent will use this value to decide outputs in this order: 1) conservation, 2) buy water rights, 3) build desalination plant. After each decision, the normalized supply-demand must be recalculated, because the values for conservation and total water rights may change, and those decisions must be taken into account in making the next decision. The remaining decision, whether to lease water rights for this year only, is made independently of the above, and depends only on the expected drought for this year.

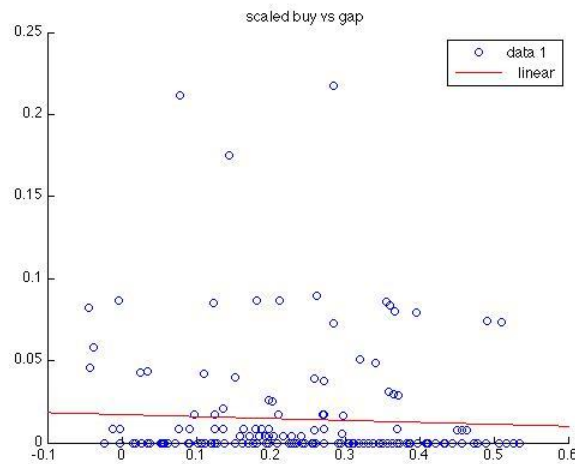


Figure 7: Purchased water rights versus supply less demand (both normalized by current demand) for municipal agents.

Ultimately the agent’s decisions are based on cues associated with conditions in the physical environment; specifically, available streamflow and growth in municipal demand. In turn, agent decisions change the intensity and location of water demand and thus influence the streamflow (or available supply of water). To capture this dynamic, the synthetic agent model is integrated with a system dynamics model of the physical environment.

Implement the Integrated Model

For this integrated model, we developed four fundamental model subsystems:

1. The System Dynamics resource model
2. The (distributed) agents and agent communication server
3. Inter-agent resource market
4. The coordination engine

We developed a general-purpose PowerSim module for the EMPaSE environment that allowed the integrated EMPaSE model to directly interface the URGSiM System Dynamics model. This module drives

the underlying PowerSim simulation by stepping the model synchronously with the EMPaSE environment. For this study, there was a mismatch between the URGSiM time step (1 month) and the integrated model time step (1 year). To address this, EMPaSE sub-cycled the URGSiM model for a full year before advancing the outer integrated model, with the integration points occurring in the month of February.

Individual agent actors (either synthetic agents or real stakeholders) are external to the integrated simulation and interact with the simulation over a network connection. We elected to structure the simulation in a distributed manner both to separate the various components and simplify development and debugging, and to simplify the transition from solely live stakeholder players to mixed live / virtual stakeholder players to solely virtual stakeholder players. To support this pattern, the EMPaSE environment provides a server module to which all agents connect. The server module converts commands received from each remote agent (XML-formatted message) into a message to inject into the EMPaSE environment. Messages or data received in reply to the original message are converted to XML-formatted responses that are sent back to the agent. The remote agents block execution (wait) between sending a message and receiving the reply, allowing us to use the same command/response communication structure both for data interchange and agent / simulation synchronization.

The final two components of the integrated simulation model are implemented within the EMPaSE environment: the inter-agent resource market and the coordination engine. The coordination engine alternates between resource exchange modes and advancement of the URGSiM resource model. The engine divides a simulation into a sequence of 1-year “rounds.” The round begins by distributing the current hydraulic state to the stakeholder agents and then waiting for all agents to report their decisions (buy/sell water rights, lease rights, etc.). Control then passes to the resource market which clears as many trades as possible. In the event of a supply (demand) shortage, the actual amount purchased (sold) is allocated among the buyers (sellers) proportionally to their original purchase (sale) request. After clearing the resource market, the coordination engine advances the URGSiM hydrology model and reports the final round results to the agents before repeating the entire process for the subsequent round.

Overview of Model Results

Several simulations were performed with the integrated model. As noted above, the synthetic agents utilized decision models developed from the gameplay during the July stakeholder meetings. Results shown here feature a baseline and three scenario runs. The baseline case simply involves simulation by URGSiM with no engagement of the agents. By setting URGSiM as the baseline, we are essentially comparing results with and without agent play. The URGSiM simulation assumes a replay of recent historic streamflows with municipal water demands increasing according to population growth projections. Irrigation is assumed constant. The three scenarios utilize the URGSiM baseline simulation modified by agent decisions. The scenarios were selected to demonstrate how agent play affects the physical environment and how uncertainty in the agent models affect results. Specific scenarios are as follows:

1. Farmer Sell: Case involves 10 farmer agents and one municipal agent. Farmer decision model is based on regression of all “farmer” play in the July meeting.
2. Farmer Limited Sell: Case involves 10 farmer agents and one municipal agent. Farmer decision model is based on regression of “farmer” play but with two outlier farmer data neglected. This results in considerably less interest by farmers to sell water.
3. More Agents: This case is similar to Case #1 except involves 20 farmer agents and one municipal agent.

Figure 8 shows model results for Case #1, Farmer Sell compared to the Baseline case. Five different environmental measures native to URGSiM are shown, the Rio Grande Compact, irrigated acres (San Felipe to Albuquerque reach), Albuquerque water use, change in aquifer storage, and minimum river flow which provide various measures of the state of the environment. The market difference graph provides an indication of the balance between agent offers to sell/lease out water versus offers to buy/lease in water.

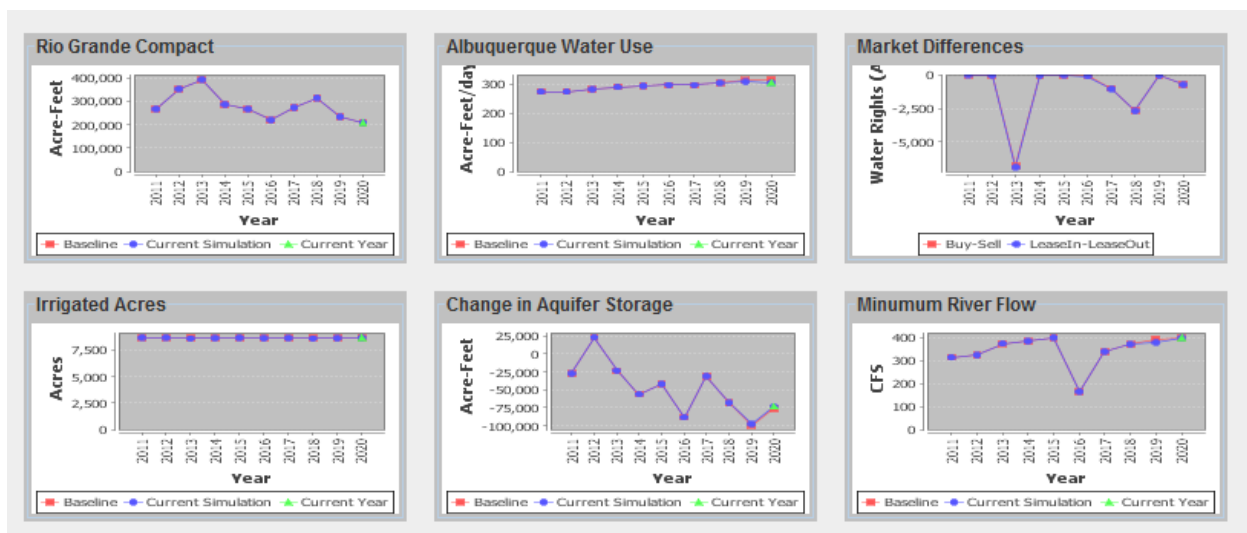


Figure 8. Integrated modeling results for the Case #1: Farmer Sell scenario (blue line) compared to the Baseline case (no agents operating). Five different measures showing the impact of agent decision on environmental conditions are given. The sixth graph shows the balance between offers to sell/lease out water to the willingness to buy/lease in water.

For the Case #1:Farmer Sell, relatively little difference is noted over the Baseline case. In total 42 AF of water was sold from farmers to the municipality while the municipality also instituted conservation measures at a level of 20% (all new homes built over the 10 year time frame had reduced water consumption of 20% over the Baseline 2010 levels). These changes were not sufficient to show up on the graphs in Figure 8. These relatively small changes are driven by the decision of the municipality to delay purchase of water rights to offset growing demand.

In the Case #2: Farmer Limited Sell case (Figure 9), a significant change is seen in Albuquerque Water Use. The municipality took measures to limit almost all new growth in consumptive water use. In this case the Municipality purchased no farmer water rights while instituted conservation measures at a level of 90%. This big increase in conservation reflects the unwillingness on the part of farmers to sell water rights as well as the stochasticity in the municipal agent’s decisions of when and how much water to purchase/conserves. While there is obviously no change in irrigated acres, there is a measureable improvement on the Rio Grande Compact (less water diverted by Albuquerque leads to a slight increase in banked water in last 2 years), improvement in groundwater depletions (less groundwater pumping means more water in the aquifer), and improved minimum flows in 2016 but reduced minimum flows in 2019 (related to complex operations of streamflows in response to demands).

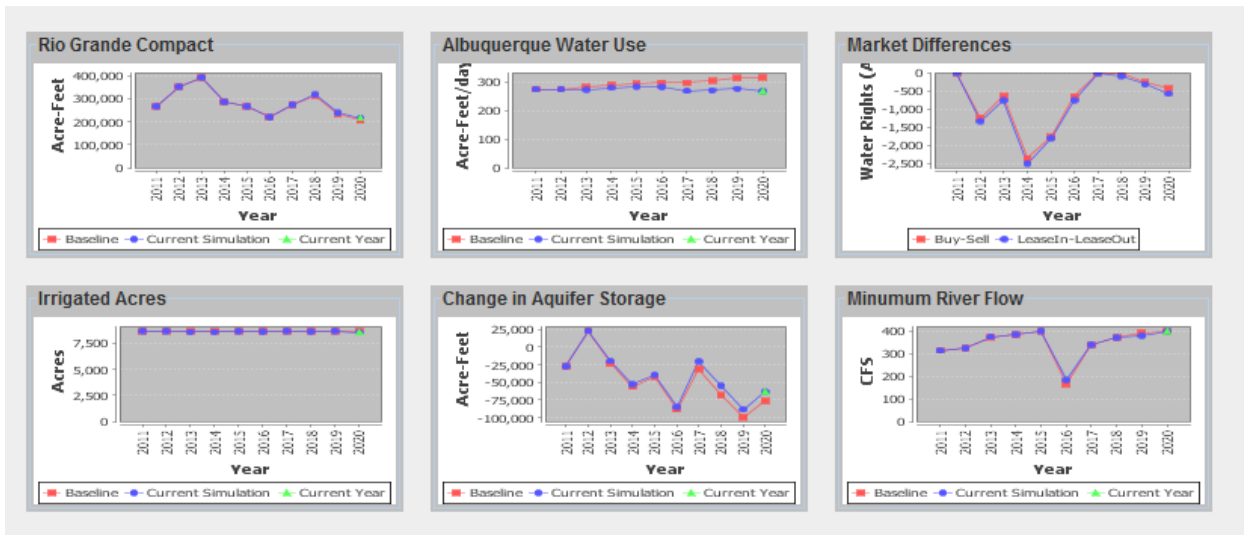


Figure 9. Integrated modeling results for the Case #2: Farmer Limited Sell scenario (blue line) compared to the Baseline case (no agents operating). Five different measures showing the impact of agent decision on environmental conditions are given. The sixth graph shows the balance between offers to sell/lease out water to the willingness to buy/lease in water.

Case #3: More Agents involved doubling the number of farmer agents using the decision model that favored the sale of water rights. In this particular simulation the municipal agent again took an aggressive approach to managing growth in water consumption. As farmers were willing to sell water the municipal agent purchased 322 AF from farmers and instituted conservation measures at a level of 60%. A commensurate reduction in irrigated acres is reflected and a decrease in Albuquerque water use is evident (Figure 10). Note that there is essentially no improvement in the Compact, as the water moved from irrigation to the city is still consumed. The conservation measures are seen to result in limited improvement in aquifer depletions.

Obviously, many other scenarios could be simulated and analyzed; however, the purpose here was simply to demonstrate the operations of the model. Results rendered from these cases appear reasonable for several reasons. Specifically, the municipal agent’s decisions changed according to the willingness of the farmer agents to sell water rights. Different farmer decision models resulted in

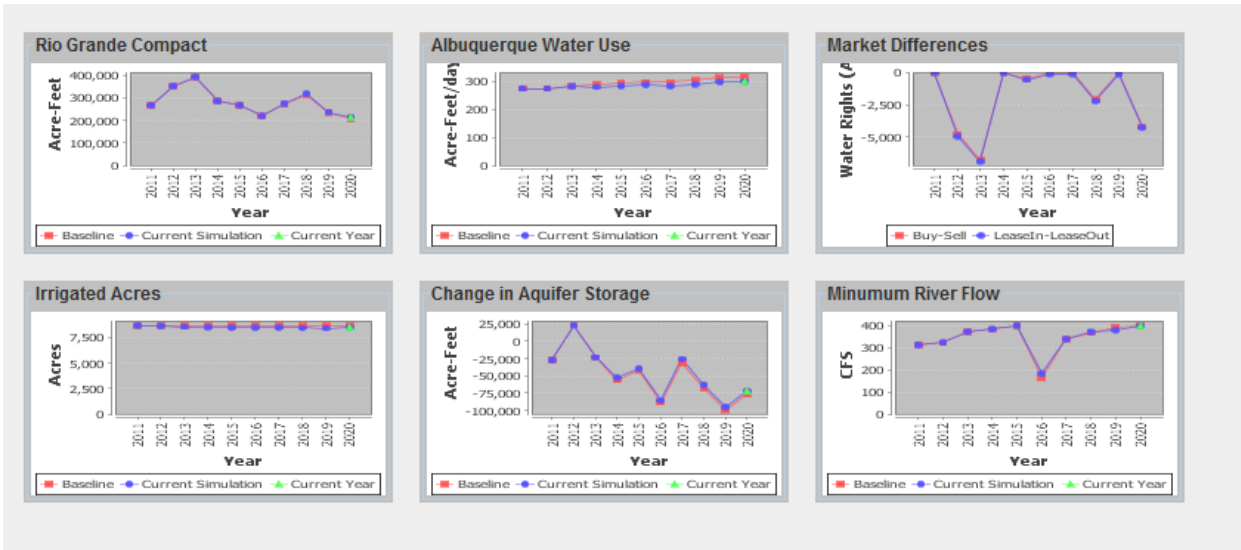


Figure 10. Integrated modeling results for the Case #3: More Agents scenario (blue line) compared to the Baseline case (no agents operating). Five different measures showing the impact of agent decision on environmental conditions are given. The sixth graph shows the balance between offers to sell/lease out water to the willingness to buy/lease in water.

different simulation outcomes. Randomness in model results was evident across simulations in the aggressiveness of the municipal agent to manage growth in water demand (the degree to which the agent bought water rights or instituted conservation measures). Finally the differences in the agent decisions were seen to have impact on the environmental model. Each of the five displayed measures were affected in a different and predictable manner.

Step Five: Develop the interface for the user with the model complex

Developing an effective user interface is about sense-making. It is about making a very complicated system and large set of data accessible to a particular type of user. We experimented with two different types of interfaces: an interface dependent upon user interaction with sets of slider bars and radio-type buttons, and a highly immersive game-type interface. The latter – the game-type interface – was in an early stage of development at the time we presented it to the users.

Development of a standard interface

In the interface developed for this engagement, each player interface has an input area on the left side of the screen and an output area on the right. Input in this case refers to data which is presented to the player; some of this data (e.g. bank balance) can be affected by the decisions that the player makes. The output area captures the player’s decision outputs – for example, how much water he decides to lease. At the bottom is a status area that is the same for all players and provides feedback such as remaining time in the round. Figure 11 shows a notional screen layout which is the same for all player types. Figure 12 and Figure 13 show the actual screens for the Farmer and Municipality, respectively.

Development of the Serious Gaming Interface

The serious gaming interface was developed with the primary purpose of creating a compelling environment for engaging stakeholders. In other words, something interesting and fun. The nature of the game was greatly influenced by the ScienceSim platform on which it was developed. As such, the serious game interface did not strictly follow the strategy used for developing the Standard Interface.

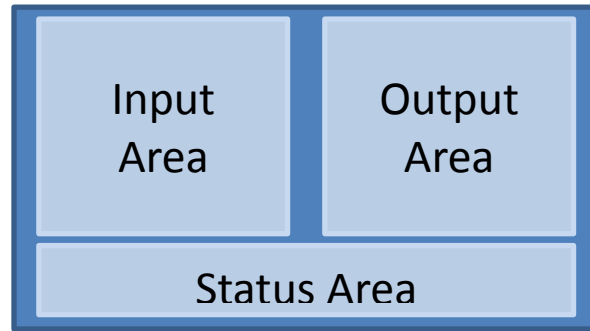


Figure 11: Notional screen layout

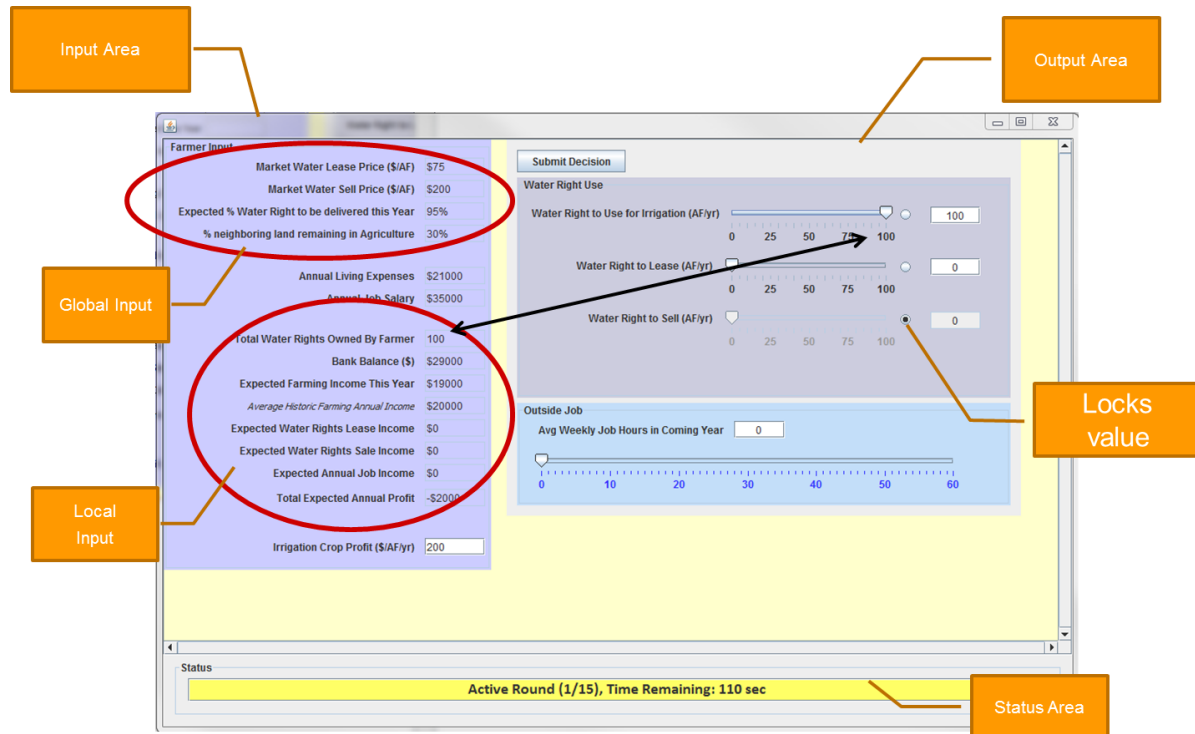


Figure 12: Farmer screen shot



Figure 13: Municipality screen shot

The serious game utilized an immersive environment in which the players controlled the physical movement of an avatar in a stylized setting representing the Middle Rio Grande (Figure 14). A player chose a livelihood and subsequently made decisions on how to grow/manage his/her business as well as how to manage the associated water rights. The system was constrained by the availability of capital and water. As play progressed players were challenged by periodic drought and economic downturns. The only requirement was that a player avoid bankruptcy, otherwise each player could pursue his own optimal outcome (e.g., maximize profit, increase acres farmed, expand the city).

Each player chose his/her career path by selecting between a farmer, developer, or industrialist. The choice ultimately determined the types of decisions with which a player was faced. A farmer decided how to cultivate the land, deciding between three different crops, alfalfa, chili, or grapes. Each have different water demands, cost to grow and payoff. For example, grapes had the greatest payoff per acre cultivated; however, they required two rounds of cultivation before they yielded a crop. Also, if the grapes went unirrigated for a round the investment would be totally lost. The developer had the option to build three different types of living spaces: single family, multi-family and estate. The cost to build, time to build, interim financing, and market value were different for each. Also, the number of units that would sell each year would differ (e.g., fewer estates are sold relative to single family). The industrialist also was faced with options of different types of plants, each with different construction costs, time to build and widget production. Players made decisions on how fast to develop based on what they valued, their capital and water resources, and their perceptions of what the future held in terms of drought and the economy.



Figure 14: Screen shots from serious game interface

The physical environment was subdivided into multiple parcels of land. Land near the river had water rights and was generally more expensive to purchase. Land further from the river had no water rights but was much cheaper to purchase. Each parcel was further divided into 12 lots. Each lot was available for development by the owner. In this way a farmer could mix the types of crops cultivated on a single parcel. Choices by players were accompanied by physical change in the environment including appearance/disappearance of crops, buildings, or houses. In this way players got a sense of how their collective decisions modified the local landscape. The Roundhouse (New Mexico State Capital Building) was used as an iconic figure on the landscape that players clicked on to control/manage the logistics of gameplay. A variety of menus and screens were provided within the environment to log player decisions, facilitate communication between players (see below), and update players on their stocks of water, capital, and annual revenue.

A game involved multiple rounds, each representing a year's duration. Each round was divided into two phases, termed build and water phases. In the build phase players made decisions on the extent of cultivation or development of their land (e.g., acres planted with grapes, or number of single-family houses to start). In the water phase players decided how to allocate their available water resources to the land (irrigate or sell the home and associated water, number of widgets to produce). At the

beginning of the next round, player bank accounts were changed by the revenue earned in the previous round and projections of the percent of their water right which will be fulfilled that year were made. Players were constrained as to how fast they could develop based on accrued capital and water rights. Gameplay was further complicated by periodic drought and economic downturn. When a drought occurred players would not receive their full water right allotment. Economic downturn reduced the prices paid for crops, homes, widgets and/or limit the total amount of any commodity purchased. Players could get in trouble by overextending their development and then getting hit with an unexpected drought or economic downturn.

The game accommodated from one to multiple players at a time. As the game evolved, players could decide to cooperate, form alliances, or work independently. Cooperation occurred through the selling/leasing property and/or water rights. Players negotiated on both the amount, price and duration of the lease.

The top image in Figure 14 shows an avatar viewing his field of chili and home in the foreground. The lower image shows the avatar viewing two different homes under construction on his parcel of land. The floating shovel is an indication that the homes have not completed construction in the current round.

Step Six: Get ‘social validity’ for the model structure and the values for key variables through engagement of stakeholders with the model through each of the two interfaces.

Stakeholder recruitment

We recruited 54 participants for a total of seven sessions, held from February through September of 2011. Recruitment procedures were discussed in the Methods section. The breakout among participant experience types is shown in Table 5. Individual interviews of other stakeholders were conducted in June. The first five sessions (February through March) exposed participants to the serious game interface. The sessions in March incorporated feedback received from the February sessions: the March participants did not see the same interface as did the February participants. July sessions exposed participants to the standard interface while September sessions involved full integrated model.

Table 5: Participants by expertise

Session date	General	Policy maker	Educator	Farmer	Activist	Municipality
2/26/11	6					
2/27/11			7			
2/28/11					5	
3/1/11		6				
3/2/11	5					
7/22/11				4		5
7/24/11				8		2
9/22/11				4		5
9/24/11				8		2
9/23/11				3		3

Overview of workshop results

Through various iterations of the project, participants were asked questions about the development, use, and application of the technology and process. Questions were asked through group and individual interviews and questionnaires conducted during research sessions. Questions fell into two general categories of inquiry:

1. Improvement of the technology functionality and design;
2. Exploration of potential uses of the technology and collaborative design/participatory process

Improvement of the technology functionality and design

During the agent modeling sessions held in July, a considerable amount of data was gathered from participants about the conceptual design of the model, the quantitative variables chosen for inclusion, model assumptions, and how these were presented through the design of the user interface. Several questions were asked in a written questionnaire administered prior to participant interaction with the user interface, in order to elicit an unbiased set of cues to validate and improve the conceptual design of the model. Table 6 shows the questions asked in the questionnaire.

After completing the modeling exercise, participants were asked to answer a number of follow-up questions regarding the design of the model. Participants responded to the following questions on a questionnaire and then discussed them as a group.

1. As you were working through the scenarios did anything stand out as:
 - a. Conceptually Missing?
 - b. Conceptually Strange or Off?
2. Are there factors that affect your water decision-making that were not included in the model? If so, which ones?
3. Were there parameters in the model that didn't make sense or were unrealistic? If so, explain.
4. How could the model be modified to be more conceptually realistic?

The data revealed a number of specific parameters that participants felt were important to water decision making, but which were not included in the model design. Municipal participants highlighted the importance of legal and regulatory factors in their decision making. In the context of the Middle Rio Grande Basin, participants identified the importance of interstate river compacts, state water laws, permitting regulations, and the risk of litigation. Participants validated that political risk is a primary concern in decision making. Participant explanations of political risk generally fell into two categories: (1) the political risk of making decisions that might result in losing one's job through electoral politics or public dissatisfaction; (2) the politics involved in upstream/downstream and senior/junior community dynamics. Overall, municipal participants did not have any major objections to the model design.

Farmer participants on the other hand provided numerous comments regarding the validity of the model design. As one participant stated "Felt kind of boxed in. Didn't incorporate enough "real life"

Table 6. Model validation questions asked of participants before interacting with the model interface

Municipal Participants	Farmer Participants
In your job, what are the top five things you and your colleagues think about when making decisions about the water supply?	List the top five things you think about when deciding how to use water on your farm
What kinds of things do you and your colleagues actually do to manage the supply of water?	What kinds of things do you actually do to manage the supply of water on your farm?
What major motivating factors affect what you decide to do to manage the water supply?	What major motivating factors affect what you decide to do to manage the water on your farm?
Do you think about the political risk of your actions when you make a decision about water? If so, how would you define “political risk”? What factors affect how risky a water decision is?	

factors.” Among the important decision factors which farmer participants felt were missing from the model, included the following:

- The ability to implement water efficiency and conservation measures (such as through crop choice, alternate growing systems, mulch, and irrigation practices)
- Water quality
- Environmental concerns
- Fluctuating parameters affecting economic costs and productivity such as crop value, labor costs, yields, etc.
- The importance of relationships between farmers, water providers, and communities
- Concerns for the well-being of communities
- Traditional uses, relationships with the land, and cultural preservation
- The accuracy of various parameters related to the leasing and selling of water rights

While these findings suggest that important decision factors are missing from the model as designed, they support and validate the importance of an iterative and collaborative process in understanding complex human interactions with resource systems and in designing decision support technologies to model them. In particular, farmer participants stressed the importance of non-economic variables in influencing their decisions. Like the “political risk” variable included in the municipal interface, such nonnumeric variables may be included in later iterations of a model. Participants themselves define and assign numeric values to the variable in order to incorporate it as a quantitative variable in the

combined agent and physical model. The ability to collaboratively identify, quantify, and then incorporate such abstract social variables into a combined SD/agent model of the resource system is an important procedural and substantive contribution to participatory modeling and decision support tool design. It enables the incorporation of critical human/resource interactions that significantly effects, but have not previously been incorporated into physical models of resource systems.

Standard Interface Design Improvements

Participants expressed a high level of difficulty in understanding and manipulating the standard interface. During data collection staff assisted participants in logging in, running scenario files, explaining the meaning of various parameters, and working through various simulations. Farmer participants expressed greater difficulty in understanding and using the standard interface than did municipal participants. One farmer stated “I didn’t even understand the contextual scenario. Nothing I do makes sense to me. I’m just playing w/ the size of my bank account.” Another wrote, “Need more time and familiarize participant with the results from manipulating the variables in this system.” This difference may be attributable to the design of the farmer interface, which presented cues as numbers as opposed to the municipal interface which presented cues in graphical form. It may also be attributable to the fact that municipal participants may have more familiarity with computerized decision support tools through their occupation and education. The difficulties expressed by participants and the high level of staff support required to operate the simulations suggest several conclusions. First, the user interface is not intuitive and certain groups of users will be more or less comfortable using a computer interface of this sort. Secondly, use of this kind of interface in decision support situations may require a high level of staff support. Future experiments might examine how to improve the design and usability of the interface. For example, numeric vs. graphical displays may affect the ease of use and modeling outcomes.

Serious Game Interface Design Improvements

Feedback on the gaming interface was collected from participant comments as they engaged with the game throughout the session, and through facilitated discussion after the game session was terminated.

The importance of the game experience as an experience (rather than as a decision-making exercise) was emphasized by players in our interface test cases. As the game interface presented by Intel was still under development, the digital environment (the ‘Middle Rio Grande valley’) was presented as an abstract environment. Users argued strongly for an environment that better reflected the ‘real’ geographic landscape. Water is tied to land, they point out, noting that water decisions were essentially and ultimately decisions about land. Land needed to be presented in some ‘real’ format, ideally corresponding to the topography of the Middle Rio Grande basin. The appearance of the avatars also engaged the participants and distracted from their direct experience with the game. The participants requested avatars more representative of the game cast of characters to replace the set the developers provided. Although the developers communicated that the avatar appearance was a function of the development environment and not directly relevant to the game performance, it clearly affected the game experience of the users. Finally, the system was difficult to use, partially as response time was very slow. Again, although the developers assured the participants that this was due to the

development phase of the project and the particular technical setup, it significantly colored the user experience.

That the gaming environment is so important to players' play reinforces our earlier suggestion that situated cognition may be an appropriate explanatory framework. It was difficult for the players to engage in this type of decision-making in an abstract environment.

In general, participants felt that the interface was not complex enough to represent the water environment in the Middle Rio Grande basin. Decision-making was based entirely on economic factors and motivations. Participants were clear that other political, social and environmental factors needed to be incorporated into the game to make it a meaningful experience.

Potential uses of the technology and collaborative design/participatory process

During sessions, participants were asked to evaluate the value and potential uses of the modeling technology and process developed through this project.

Participants in the September follow-up session were asked about the value of developing and using a model that combines agent models of human factors with a system dynamic model of the physical watershed. Specifically they were asked: What benefits are there to using a model that incorporates agent models with a system dynamic model of a watershed?

Participants unanimously agreed that there were significant potential benefits to the use of the combined model. Participants stated that the model demonstrates the systemic effects of certain stakeholder decisions that are otherwise not visible. This includes individual behaviors that in aggregate greatly affect the physical system, such as agricultural and household water use. Participants stated that this has important implications for demonstrating complex and abstract ideas about how individual behaviors might be modified to achieve systemic outcomes. This could be used in numerous applications in public education, water conservation initiatives, farm and irrigation policies, and state and local water supply management. In the context of decision support and conflict resolution, the combined model and process help to identify critical stakeholders, their interests, and behaviors. Participants stated that this has important implications for interest based conflict resolution, coalition building, and relationship building and stakeholders gain a greater understanding of and empathy for each other.

During the September follow-up and February/March sessions with Intel, participants were asked the following question: In what kinds of water planning and management situations might this tool (the model) and the modeling process be useful? Participants identified a wide number of potential applications and audiences for the decision support architecture developed in this project

Participants identified several types of policy-related applications. The standard interface could be used by state or local entities to understand different water policy scenarios for lawmaking or management. Both the standard interface and the immersive game environment might be used by organizations such as government agencies and non-profits to devise and discuss different policy scenarios. Use of the

model in this way could stimulate thinking about how different stakeholders and aspects of the physical system may respond under different kinds of scenarios.

In legal environments, participants suggested the standard interface could be used to educate judicial and law enforcement staff about water issues, and to give weight to claims in water related cases. It might also be used in alternative dispute resolution processes such as mediation and settlement negotiations.

There were several community education applications envisioned by participants. These included the use of both the standard and the immersive interface by municipalities, water service providers, and non-profits to raise awareness about water issues and teach the public about water use and conservation. Both interfaces could be used in public venues such as libraries, farmers markets, or public meetings, or in retreat settings to educate and stimulate thinking on the water system. Both interfaces could also be used by acequia associations and farmers to look at impacts of different water management decisions and to facilitate and stimulate discussion of different water management scenarios and identify opportunities for cooperation and coalition building.

In classroom education environments, the gaming interface would be appropriate for high school and college level students to teach them about water rights, conservation, and water policy. It would need to be simplified for use at an elementary level. It also could be used as part of a classroom curricula implemented by city water conservation office.

Summary

The environment in which we operate is comprised of a complex set of physical and social systems that interact over a range of spatial and temporal scales. These systems are continually evolving in response to changing climatic patterns, land use practices and the increasing intervention of humans. Thus, intuition and experience alone are insufficient to effectively manage our resources; rather, quantitative and integrated modeling systems are required to inform the decision process. However, developing environmental management models that are both scientifically sound and publicly acceptable is often fraught with difficulty. If such models are developed “behind closed doors”, their operation, application and utility can appear obscure to stakeholders. Rather, an open and participatory model development process can help overcome such problems by building familiarity, confidence and acceptance in the models, while allowing a more diverse group of participants to engage in the planning process.

Our working hypothesis is that stakeholders can produce a broader set of potentially acceptable and feasible solutions (i.e. policies) for shaping a sustainable future with a more complete understanding of both the natural system and the associated socio-cultural and political systems. We posit that this “better understanding” will be most effectively achieved through broad stakeholder engagement with tools that can present data and information related to the linkages between water, development, social/environmental/cultural values, and the operation of existing institutions.

Our exploration of this hypothesis began with a look for related studies; in particular, we reviewed the literature to develop a better understanding of participatory modeling. We were particularly looking for

detail on how stakeholders were identified, how roles were defined for the game, how the game was actually played, and how data was collected. In almost every exercise of participatory modeling, all of these methodological steps were very poorly documented.

The processes defined in the literature constructed the games based largely on secondary source research and interviews with local participants. The published works on this topic are unclear as to method. They provided no information as to what they asked in the interviews (no sample protocols or descriptions of questions), what data they collected during the observations of the role plays nor how they collected that data. We believe this work makes a significant contribution to the literature on the participatory modeling process through our documentation of our data collection methods.

We augment the 'standard' participatory modeling process in two important ways. First, in addition to the collection of information through a role-playing games, we drew heavily on the knowledge held by subject matter experts (SMEs), including those who were directly associated with the project and others we identified in the community. Second, we believe that our work has made a significant contribution to the design and development of decision support tools. Our exploration of the use of participatory modeling led us to construct an integrated modeling engine by coupling a systems dynamics model of the natural resource structure of the Middle Rio Grande Basin with an agent-based model of two key decision-makers in the region: farmers and municipalities. We used the participatory process to develop a socially validated rule set for these player types. This allowed us to create computational 'players' such that there would always be a sufficient number of players in any round to significantly impact the natural resource base (represented in the systems dynamics model), no matter how many (or how few) human players there were. Several scenarios were "played out" with the integrated model demonstrating system dynamics both with and without agent participation. Results indicate that agents responded to other agent decisions and changes in the environment but with a measure of stochasticity.

Our exploration was further expanded to consider the use of two different types of user engagement platforms (i.e., interfaces). One involved a "standard interface" in which stakeholders engaged through manipulation of radio buttons and slider bars and received feedback through graphs and charts. The other interface involved "serious gaming" which placed the stakeholder in an immersive gaming environment. Feedback on the serious gaming interface suggests its primary value was in an educational context. Policy application is complicated by the fact that user demands of such an interface with the associated computational, financial, and development demands may make it impractical for a water community to develop on its own.

Our stakeholders identified many uses for the participatory process, which includes both the computational tool and the engagement with it. Uses were identified in policy-making, legal, educational, and community education environments. However, all participants were aware of the limitations placed upon the tool use by the required technology – computers and connectivity – and the amount of time required to teach the process as it is currently implemented.

Path forward

This project has demonstrated a new approach to decision support modeling through stakeholder engagement with traditional and novel data capture techniques to develop agent models integrated with system models of the physical environment. The serious gaming platform demonstrates a radically new means of participatory resource planning allowing remote access, automated data capture, and intrigue to the next generation.

However, there is much work remaining to do. This particular project would benefit from several additional development spirals coordinated with stakeholder engagement. With each spiral additional detail in terms of physical and human behavioral processes would be added to the model. Utilization of process based behavioral models rather than empirically-based models would improve fidelity of the modeling. Other improvements could include extension of modeling to additional river reaches, the addition of hundreds to thousands of agents, and improvements to the resource market. The stakeholder engagement experience could also be enhanced by expanding the user interface.

There are three specific opportunities to utilize the tools and thinking developed under this project. Opportunity to engage is immediate and is likely to take 5 years to reach full potential. These opportunities include:

1. Science, Technology, Engineering and Mathematics (STEP) educational programs in collaboration with Intel Corporation and publishing companies for K-12.
2. DOE's Climate Science Program supporting Integrated Assessment modeling.
3. Other Federal agencies facing difficult value laden decisions on resource allocation and sustainability.

Appendix A: Serious games and game-based learning

Part of this project involved an exploration of the consequences of two different mechanisms of engagement with computational simulations: a standard slider bar/radio knob interface, and the immersive environment offered by what are called ‘serious games.’ Given the widespread interest in games and gaming environments, and the involvement of Intel in our project, we felt it worthwhile to explore the nature of games – serious games in particular, as they are often used for learning – and learn how they differ from other forms of learning.

We began by recognizing a distinction in the gaming literature between serious games and game-based learning. For the sake of fairness, we do need to note that this distinction between serious games and game-based learning is not recognized by everyone.²⁸ However, we argue here that the distinctions are more than semantic. They draw upon different intellectual traditions and make distinctly different but complementary contributions to the use of digitally based media in learning environments.

In terms of this project, the Intel platform is being developed in a serious game tradition, but the standard interface would be from a digitally-based learning tradition.

Some Definitions

Since discussions about serious games involve terms that may seem familiar but are used in specialized ways (such as ‘game,’ for example) and the two traditions may use the same term in different ways, a discussion of definitions is in order. The common thread within both approaches to learning is the use of games, so that seems an appropriate place to begin.

What is a Game?

There are a number of definitions of *game*. The traditional definitions of game are almost all tied to fun. Fun is either the goal of the game (‘to have fun’) or it is used to describe the nature of the activity required for a game.

The Oxford English Dictionary defines “game” as: “1.1 Amusement, delight, fun, mirth, sport.” This is followed by (in addition to its etymology) a literary explanation of the essential meaning of a game, which can be summed up as “No game = no fun.”²⁹ Another dictionary (Webster) defines ‘game’ in a similar manner: again, the first definition of game is essentially connected to fun, this time articulated as ‘diversion’ and ‘amusement’:

GAME

1a (1) : activity engaged in for diversion or amusement : play (2) : the equipment for a game b : often derisive or mocking jesting : fun, sport <make game of a nervous player>
2 a : a procedure or strategy for gaining an end : tactic b : an illegal or shady scheme or maneuver : racket

²⁸ Corti, K. (2006) Games-based Learning; a serious business application. PIXELearning Limited. [www.pixelearning.com/docs/games_basedlearning_pixelearning.pdf]

²⁹ The Oxford English Dictionary

3 a (1) : a physical or mental competition conducted according to rules with the participants in direct opposition to each other (2) : a division of a larger contest (3) : the number of points necessary to win (4) : points scored in certain card games (as in all fours) by a player whose cards count up the highest (5) : the manner of playing in a contest (6) : the set of rules governing a game (7) : a particular aspect or phase of play in a game or sport <a football team's kicking game> b plural : organized athletics c (1) : a field of gainful activity : line <the newspaper game> (2) : any activity undertaken or regarded as a contest involving rivalry, strategy, or struggle <the dating game> <the game of politics>; also : the course or period of such an activity <got into aviation early in the game> (3) : area of expertise : specialty 3 <comedy is not my game> 30

The emphasis on fun would suggest that a 'serious game' is an oxymoron and not possible. However, we see that in the third definition of *game* above we get more of a formalism, which could potentially allow serious games. It really is only when we get the creation of games specifically educational or learning-oriented in nature that the notion of 'fun' drops out of the heart of the definition of a game.

This is an interesting change in focus for games. Games that are defined by fun are defined by the state of the player. The player must have fun either during the playing of the game or because he played the game. The third definition from Webster removes the player altogether. *Any competition-driven activity with a formalized rule set can be termed a game.* This allows the development of a focus on the game as artifact, separate from any player-based experience. Serious games become possible.

We note that the distinction between those who speak of serious games and those who speak of digital-based learning use the term 'game' differently. Those who speak of serious games are focusing on the artifact, on the formalism – a competition-driven activity with a formalized rule set. Those interested in digital-based learning focus on changes in the player, potentially (but not necessarily) using fun in the process.

If we look at some of the definitions in the specific context of serious games, we clearly see the DGBL/serious games distinction just in how they lay out their vocabularies. Michael and Chen's definition of games from *Serious Games*, a foundational text in the field, follows:

Games are a voluntary activity, obviously separate from real life, creating an imaginary world that may or may not have any relation to real life and that absorbs the player's full attention. Games are played out within a specific time and place, are played according to established rules, and create social groups out of their players.³¹

This definition of game pays no attention to learning or any other changes in the player. The focus is on creating an environment of a particular type, conforming to certain rules of construction.

In the same tradition, Dempsey *et al* describe a game as "...a set of activities involving one or more players. It has goals, constraints, payoffs and consequences. A game is rule-guided and artificial in some respects. Finally, a game involves some aspect of competition, even if that competition is with

³⁰ <http://www.merriam-webster.com/dictionary/game>

³¹ Michael, D. & Chen, S. (2005) *Serious games: Games that educate, train, and inform*. Boston, MA.: Thomson Course Technology.

oneself.”³² Others emphasize the fantasy or imaginative nature of games³³ and the competitive nature of games.³⁴

Prensky³⁵ identifies, and claims, that computer games are characterized by six “structural elements” that come together to create the engaging experience he argues is the key to using computer games as effective learning tools. The elements are: rules, conflict (competition, challenge, opposition), goals (objectives), interaction, outcomes (feedback), representation (story).³⁶ Note that in all these cases the focus is on the game as an artifact. The player is conspicuously absent.

A Serious Game

*Even a brief survey of the literature soon reveals that there seems to be as many definitions available as there are actors involved, but most agree on a core meaning that serious games are (digital) games used for purposes other than mere entertainment.*³⁷

The term ‘serious game,’ i.e. a set of formal actions which conform to certain requirements, may have its origin in the 1970 book *Serious Games* by Clark C. Abt,. However, he may have coined the term earlier: he was clearly thinking of games in those terms through the 1960s. This is an often quoted excerpt from an interview he did with Time Magazine:

Too much business management training is “inefficient and outmoded” says Abt, because the trainees are forced to sit idly by and watch others. “People like to act,” says Abt. “They like to make something happen.” They also like to play games.³⁸

Abt argued that games and simulations could train decision-makers across the public and private sectors, and could be used for general education. He also suggested that they could be used to improve interpersonal relationships. Abt’s and other early practitioners of games of this type do not clearly distinguish between serious games and game-based learning approaches in the terms we articulated earlier in this discussion. That is a distinction that emerged as the field matured.

Today, perhaps one of the most often cited texts on serious games is that which we referenced above, Michael and Chen’s book, *Serious Games*. In it they define serious games in several different ways. In our earlier quote from them, they spoke of serious games as voluntary activities “obviously separate from real life” and played out according to a formal set of rules. They go on to say that

³² Dempsey JV, Lucassen BA, Haynes LL, Casey MS (1996). Instructional applications of computer games. Paper presented to the American Educational Research Association, 8–12 April 1996, New York. ERIC Document Reproduction Service No. ED 394 500. page 2.

³³ Fabricatore C (2000). Learning and videogames: an unexploited synergy. At www.learndev.org/dl/FabricatoreAECT2000.pdf.

³⁴ Randel JM, Morris BA, Wetzel CD, Whitehill BV (1992). The effectiveness of games for educational purposes: a review of recent research. *Simulation and Gaming*, 23(3), 261–276

³⁵ Prensky 2001, *Digital game-based learning*. New York: McGraw-Hill page 119-119

³⁶ Prensky 2001, *Digital game-based learning*. New York: McGraw-Hill

³⁷ Tarja Susi, Mikael Johannesson, Per Backlund, *Serious Games – An Overview*,

³⁸ Time Magazine, September 16, 1966

In general terms, serious games are associated with ‘games for purposes other than entertainment’... Serious games encompass the same goals as edutainment, but extend far beyond teaching facts and rote memorization, and instead include all aspects of education – teaching, training, and informing – and at all ages.³⁹

Parts of this definition have been picked up by others. For example, Michigan State University offers a master’s degree in serious games and defines them as: “...games with purpose beyond just providing entertainment.”⁴⁰ Note the centrality of the game, not the learner.

The *just* in the Michigan State University’s description (“beyond just providing entertainment”) tells us that ‘fun’ is not necessarily completely absent from a serious game. Most of the *serious game* literature, despite its name, argues that serious games either must be, or at least ought to be, entertaining and fun. However, the fun or entertainment is not the end state: it is a mechanism to engage the player in order for him to be educated/trained/etc. The focus is still on the nature and construction of the artifact.

Play

How does an actor engage with a serious game? Through play, of course. Well – not so fast. The serious game literature rarely explicitly addresses play – what it is, what it does, how one engages in it. (Note that for DGBL, the key activity is learning, not playing. We will address this in more detail later.) There are even a number of authors who omit the word entirely. They use language that focuses entirely on the game itself. Again, the game as artifact becomes central: the player is absent.

The OED defines play as “Exercise, brisk or free movement of action”. The first Merriam-Webster definition defines play as: “1a: to engage in sport or recreation”⁴¹. Further down we find: “4a : to engage or take part in a game *b* : to perform in a position in a specified manner ... *c* : to perform an action during one's turn in a game *d* : gamble *e* (1) : to behave or conduct oneself in a specified way <play safe> (2) : to feign a specified state or quality <play dead> (3) : to take part in or assent to some activity”⁴².

The first definition is the most traditional, or colloquial definition of term, with a very ‘not serious’ sense to the term. It contrasts with most definitions of play in the serious game literature. This literature tends to implicitly describe playing in terms of conduct according to rules and a goal. Formal definitions are very hard to find.

Fun

Fun is also a rarely defined that is often the subject of debate in the literature: is it necessary to have fun for a serious game to be effective? Prensky describes fun as: “the sense of enjoyment and pleasure; puts us in a relaxed receptive frame of mind for learning. “ We will discuss fun as it relates to games in

³⁹ Michael, D. & Chen, S. (2005) Serious games: Games that educate, train, and inform. Boston, MA.: Thomson Course Technology.

⁴⁰ <http://seriousgames.msu.edu/>

⁴¹ <http://www.merriam-webster.com/dictionary/play?show=1&t=1290543246>

⁴² <http://www.merriam-webster.com/dictionary/play?show=1&t=1290543246>

greater detail later on, however, it is interesting to note that this was the only definition for fun in the serious game or game-based learning context we were able to find.

Game Based Learning

*Game based learning (GBL) is a branch of serious games that deals with applications that have defined learning outcomes. Generally they are designed in order to balance the subject matter with the gameplay and the ability of the player to retain and apply said subject matter to the real world.*⁴³

While this is an interesting definition, it is one that ultimately fails to distinguish adequately between the game-based learning and serious games. This attitude, is however, not uncommon amongst the *serious game* advocates who argue that the game as the artifact is more important than what you do with it. Others argue that the differences are merely semantic.⁴⁴ We however, see them as distinctly different.

Prensky⁴⁵ argues that DGBL is based primarily on two key premises: 1) that digital media has its own *language*, that most people of *learning age* today have developed new thinking patterns based on their immersion in digital media. Therefore much of today's population are 'native speakers' in the *language* of digital media. 2) This same population has been brought up on/intimately familiarized with a "radically new form of computer and video game play", and "this new form of entertainment has shaped their preferences and abilities and offers an enormous potential for their learning, both as children and as adults."⁴⁶ The argument is that this "native speak" translates to better performance in games that are based in digital media, and allows these 'native speakers' to better experience the three-dimensional, real environments of computer gaming.

The 'native speak' argument is one that frequently comes up both in serious game and in DGBL language, although more frequently in the latter. However, from a GBL standpoint, digital media is simply a new language and medium through which the same learning processes as we have previously experienced through hard copy or other media can occur.

In neither case, however, is the digital native argument essential. Related arguments suggest that digital media, and even computer games (this might come back to our argument about what a game is) can be used as a means of developing player confidence and abilities in spatial modeling, design composition, and form creation for application in architecture and the like.^{47,48} Along the same lines, Guy et al.⁴⁹

⁴³ en.wikipedia.org

⁴⁴ Corti, K. (2006) Games-based Learning; a serious business application. PIXELearning Limited. [www.pixelearning.com/docs/games_basedlearning_pixelearning.pdf]

⁴⁵ Prensky, M. (2001) Digital Natives, digital immigrants. .lwww.marcprensky.com/writing/Prensky%20-%20Digital%20Natives,%20 Digital%20Immigrants%20-%20Part1.pdf

⁴⁶ Prensky, M. (2001) Digital Natives, digital immigrants. .lwww.marcprensky.com/writing/Prensky%20-%20Digital%20Natives,%20 Digital%20Immigrants%20-%20Part1.pdf

⁴⁷ Coyne, R. (2003) Mindless repetition: Learning from computer games. *Design Studies*, 24(3), 199–212.

⁴⁸ Radford, A. (2000) Games and learning about form in architecture. *Automation in Construction*, 9(4), 379–385.

⁴⁹ Guy, B., Bidwell, N. J. & Musumeci, P. (2005) *Gameplan: Serious gaming for place making*. IE2005: Proceedings of the Second Australasian Conference on Interactive Entertainment. Sydney, Australia: Creativity & Cognition Studios Press, 252.

suggest playing with three-dimensional computational models as a means for enhancing town planning. DeLisi and Wolford⁵⁰ report on how ‘the capacity for mental rotation’ can be improved by playing computer-based games such as Tetris.

Game-based learning advocates tend to advocate a constructivist approach to learning. The learner is the focus of game-based learning, not the game. For example, in the serious game literature, the (potentially) engrossing nature of games is described as an attribute of the game which makes it a better ‘teacher.’ That same attribute (the engrossing nature of the game) is described by those in the GBL camp as a means to draw the learner into the game. An engaged learner is essential for learning in a constructivist approach, so the engrossing nature of the game is essential for learning. So the same attribute (the engrossing nature of the game) can be seen to have value as it enhances the artifact (the game) by making it a better teacher *and* enhancing the learning process by engaging the learner in the process. The attribute is necessary in both cases –but for very different reasons.

How do we learn from, or with the aid of, games?

As we have discussed in previous sections, there are clear differences in the underlying theories of learning between a serious game approach and a game-based learning approach. These differences have led to situations in which both camps may embrace the same or similar aspects of process or games but for very different reasons. The difference in perspective on the engrossing nature of the game that we saw in the previous section is a good example of this. The difference in the definition of game and of play also comes into play here. Advocates of a serious game approach would consider someone to be playing a serious game if they were in Second Life, in a Second Life classroom, listening to their professor’s avatar give a physics lecture. While this activity fits some of the definitions of gameplay, it is decidedly not game-based learning. Furthermore, if the student learned something from this time spent (whatever ‘learned’ might mean), we would need to assess if and how the artifact of the game was of benefit. Would the student have learned more? less? different things? additional things? If he were listening to the lecture from a ‘real’ person rather than from an avatar? Was the *game* an essential element that engaged the student at a new level and allowed to professor (the active agent here) greater access and ability to disseminate knowledge?

There are three general schools of learning theory: behaviorism, cognitivism and constructivism. Behaviorism has been out of favor in the mainstream for quiet sometime. What most in the United States would identify as *the traditional* teaching model is based around a cognitivist approach where information is disseminated from an authority to the learners. There are two primary assumptions on which the cognitivist school is based: the memory system is an active organized processor of information (much like a computer) and prior knowledge plays an important role in learning, as knowledge exists in “bundles” or parts that function like building blocks. Lastly we have constructivism, which is often associated with more recent learning approaches. It is differentiated by its assumption that the learner is the active agent, content is relative, every learner has a unique understanding of it, and thus a unique learning experience. Situated cognition, in which the *knowing* is seen as inseparable

⁵⁰ De Lisi, R. & Wolford, J.L. (2002) Improving children’s mental rotation accuracy with computer game playing. *Journal of Genetic Psychology*, 163(3), 172–182.

from the *doing* is a form of constructivism in which learning is measured through effective application in the real world rather than the abstract accumulation of *knowledge*, as what is *known* depends on the situation, the agents present, and the context.

Our discussion here has associated the *serious game* approach primarily with cognitivism and the game based learning approaches with constructivism. Participatory modeling would fall into the constructivist, situated cognition camp.

We would expect these differences in approaches to learning to continue to play out in the claims that games can facilitate learning, and when, where and how their use in the learning process would be most effective. However, most of the literature we have seen focuses on documentation of improvements in *performance levels* rather than exploring how different game-based interventions can lead to different *learning outcomes*.

Simulations are the game type which seem to have the best results in performance enhancement. They provide the learner instant feedback, clear goals, and a 'correct' way to get there (i.e. there are rules). A flight simulator is a good example. However, although these studies measure enhancements in performance, they generally do not assess the impact of the simulation (or game) on the learning *process*.

There have been experiments⁵¹ involving "attention training" that seem to show that even 'nonsystematic experience' with digital games improves attention behavior with children. This broad statement contradicts some of the stated concerns by skeptics that digital media kills attention span. On the other hand this could be a somewhat circular argument since both DGBL and serious game advocates argue that a digital game's ability to engage the players is a very important aspect of a successful game.

So how do computer-based games enhance the learning process? Squire and Jenkins⁵² argue that games are a good way of creating cognitive links between different concepts, in particular with respect to history. There is also some evidence and suggestion^{53, 54, 55} that digital games improve self-awareness and self-monitoring skills through their ability to give constant feedback, enhance problem recognition, problem solving skills, and decision-making, and improve both short and long-term memory. There is also the claim that digital games can improve collaboration, negotiation and group-decision making

⁵¹ Navarro, J. I., Marchena, E., Alcalde, C., Ruiz, G., Llorens, I. & Aguilar, M. (2003) Improving attention behavior in primary and secondary school children with a computer assisted instruction procedure. *International Journal of Psychology* 38(6), 359–365.

⁵² Squire, K. & Jenkins, H. (2003) Harnessing the power of games in education. *Insight*, 3(1), 5-33.

⁵³ ELSPA (2006) *Unlimited learning: Computer and video games in the learning landscape*. Entertainment and Leisure Software Publishers Association, ELSPA.

[www.elspa.com/assets/files/u/unlimitedlearningtheroleofcomputerandvideogamesint_344.pdf]

⁵⁴ Mitchell, A. & Savill-Smith, C. (2004) *The use of computer and video games for learning: A review of the literature*. Learning and Skills Development Agency.

[<https://crm.isnlearning.org.uk/user/login.aspx?code=041529&P=041529PD&action=pdfdl&src=WEBGEN>]

⁵⁵ Rieber, L.P. (1996) Seriously considering play: Designing interactive learning environments based on the blending of microworlds, simulations, and games. *Educational Technology Research and Development*, 44(2), 43–58.

skills, in contrast to the skeptics who suggest that digital-media has a desocializing effect. Again, we might ask, is collaboration and negotiation improved any more by engaging with digital media than it would be through live ground games and activities? Is this merely digital window dressing? It is here that participatory modeling in general and our project in particular may make a significant contribution.

There were some early studies done in the 1990s (e.g. Randel et al.⁵⁶ and Dempsey et al.⁵⁷) that tried to compare the effectiveness of game and technology based learning and instruction versus conventional approaches. But these studies, like many others, were largely inconclusive, with Mitchel and Savill-Smith saying in reference to that era of study on game/technology based learning: “it appears that few firm conclusions can be drawn...”⁵⁸

It is generally agreed that a virtual, digital interactive experience can generate a high level of engagement often by immersing the player in a fictitious environment. “Rich visual and spatial aesthetics draw you into extravagant fantasy worlds that nevertheless seem very real on their own terms.”⁵⁹ Even fun is not something to be enjoyed in its own right but is important in computer games only in that it helps keep the player engaged As Prensky put it,

Unlike many other game environments, complex computer games provide a complete, interactive virtual playing environment and ambience information creates an immersive experience, sustaining interest in the game.⁶⁰

While this begs the question of how much attention factors into learning and achievement in conventional learning environments, it does suggest that the immersion and associated ease of engagement allows the player/learner to focus a greater amount of cognitive capabilities on the task or and less on keeping ourselves focused on the problem at hand. Further investigation in this area would be useful.

Attewell and Savill-Smith created a chart derived from Prensky’s list of elements which make computer games engaging, contrasting those which contribute to the quality of the game *qua* artifact, and those which contribute to the player’s engagement in the game (effect a change in the player somehow).⁶¹

However, there is agreement on little else.

As we move through the literature on the subject, we find that the immersive, attention-getting and – keeping aspects of computer-based games seems to be their most essential quality. The “flow state”⁶² is

⁵⁶ The effectiveness of games for educational purposes: a review of recent research. *Simulation and Gaming*, 23(3)

⁵⁷ Dempsey JV, Rasmussen K, Lucassen B (1994). Instructional gaming: implications for instructional technology. Paper presented at the Annual Meeting of the Association for Educational Communications and Technology, 16–20 February 1994, Nashville, TN

⁵⁸ Mitchell, A. & Savill-Smith, C. (2004) The use of computer and video games for learning: A review of the literature. Learning and Skills Development Agency.

⁵⁹ Poole S (2000). *Trigger happy, video games and the entertainment revolution*. New York: Arcade Publishing

⁶⁰ Prensky 2001, *Digital game-based learning*. New York: McGraw-Hill

⁶¹ Attewell J, Savill-Smith C (2003). Mobile learning and social inclusion – focusing on learners and learning. Paper presented to the MLEARN 2003 Conference – Learning with Mobile Devices, 19–20 May 2003, London

⁶² Csikszentmihalyi M (1990). *Flow, the psychology of optimal experience*. USA: Harper & Row

<i>How characteristics contribute to the quality of the computer game</i>	<i>How characteristics contribute to players' engagement</i>
Fun	Enjoyment and pleasure
Play	Intense and passionate involvement
Rules	Structure
Goals	Motivation
Interaction	Doing {i.e.. the activity}
Outcomes and feedback	Learning
Adaptive	Flow
Winning	Ego gratification
Conflict/competition/challenge and opposition	Adrenaline
Problem Solving	Sparks creativity
Interaction	Social groups
Representation and a story	Emotion

sometimes cited as the goal of this highly-immersive design. This is, “a state of intense concentration and passionate involvement, where challenges are closely geared to ability.” The learner is given tasks just at the edge of his ability to complete, and immediate feedback on success and failure allow him to advance rapidly and smoothly.

However, if it were true that creating an engaging environment were all that were necessary for learning, computer-based games should be an effective tool for teaching anything. We would all learn better in Second Life than we would in the ‘real world.’ Obviously, this is a nonsensical statement. Perhaps the correct formulation is that the immersive environment is necessary but not sufficient for digitally based games to teach effectively.

An early review of pre-1991 studies⁶³ found that serious games (for the most part not computer based) found differing levels of effectiveness depending on the subject matter they attempted to address. At that point, in what we could call the “pre-immersion” era, they reported that serious games worked best for teaching math, physics and language arts. They found that they worked rather poorly at teaching social studies, biology and logic. A more recent paper put out by Griffith agrees that games are most effective when “designed to address a specific problem or to teach a certain skill”⁶⁴Randel suggested that games were more effective when the content targeted for teaching was very specific, and the objective very precise. Kirriemuir⁶⁵ makes similar claims. In other words, they are good for helping students figure out how to solve very specific problems, with very specific *right* answers.

Din and Calao⁶⁶ argue that not only must the objectives be specific, but the in-game tasks “appropriate to learner’s level of maturity and skill.” Further, there is an argument that these types of games cannot

⁶³ Randel JM, Morris BA, Wetzel CD, Whitehill BV (1992). The effectiveness of games for educational purposes: a review of recent research. *Simulation and Gaming*, 23(3), 261–276

⁶⁴ Griffiths MD (2002b). The educational benefits of videogames. *Education and Health*, 20(3), 47.

⁶⁵ Kirriemuir J (2002). The relevance of video games and gaming consoles to the higher and further education learning experience. April 2002. Techwatch Report TSW 02.01. At www.jisc.ac.uk/index.cfm?name=techwatch_report_0201,

⁶⁶ Din and Calao J (2001). The effects of playing educational video games on kindergarten achievement. *Child Study Journal*, 31(1), 95–102.

impart entirely new skill-sets, and that players must have some pre-existing base-level of familiarity of with the material prior to engaging with the game.⁶⁷ Simulations are a good example of this. They try to teach a very specific skill, and there is a “right answer.” However they are not static: through rules, computer games allow manipulation of objects, supporting development towards levels of proficiency.⁶⁸ Simulations are arguably flexible and complex enough to account for different learning styles.⁶⁹⁷⁰ They can purportedly broaden the user’s exposure to material by ‘simulating’ different people, perspectives and experiences.⁷¹ Kirriemuir⁷² suggests that the post-simulation review and social interaction by the various participants is meaningful and develops collaborative social skills. However, here it would seem that the simulation is simply a surrogate for any event that participants could discuss. It need not necessarily be a computational game.

Filipczak⁷³ simply suggests that they allow the learner to play decision maker and try different approaches with instant, clear feedback. He suggests that as skills improve, reactions to the simulation get faster, and then decision making gets faster, “In short, the designer puts the user in a learning environment and then increases the complexity of the situations.”⁷⁴

*The instant feedback and risk-free environment invite exploration and experimentation, stimulating curiosity, discovery learning and perseverance.*⁷⁵

Simulations, as a very constrained game type, may be the best type of serious game to teach a very targeted, bounded skill in a simulated, essential, environment. In a simulation, feedback is instant, and the learner has the opportunity to continually “pick himself up” and try again. There is also the evidence that the social interactions around a simulation are of some value. However, they are not a ground-zero teacher: you can’t step into a flight simulator and expect to get anything out of it if you haven’t read the manual, or received any kind of “conventional” pre-flight training, even if it’s very limited, and the simulation is very simple.

⁶⁷ Subrahmanyam K, Greenfield P, Kraut R, Gross E (2001). The impact of computer use on children’s and adolescents’ development. *Journal of Applied Developmental Psychology*, 22(1), 7–30.

⁶⁸ Fabricatore C (2000). Learning and videogames: an unexploited synergy. At www.learndev.org/dl/FabricatoreAECT2000.pdf,

⁶⁹ Kirriemuir J (2002). The relevance of video games and gaming consoles to the higher and further education learning experience. April 2002. Techwatch Report TSW 02.01. At www.jisc.ac.uk/index.cfm?name=techwatch_report_0201,

⁷⁰ Sedighian K (1994). Playing styles for computer and video games. In T Ottman and I Tomek (eds) *Proceedings of the ED-MEDIA 94 World Conference on Educational Multimedia and Hypermedia*. Panel discussion ‘Can electronic games make a positive contribution to the learning of mathematics and science in the intermediate classroom?’ AACE (Association for the Advancement of Computing in Education), Vancouver, Canada, 25–30 June 1994.

⁷¹ Berson MJ (1996) Effectiveness of computer technology in social studies: a review of the literature. *Journal of Research on Computing in Education*, 28(4), 486–499.

⁷² Kirriemuir J (2002). The relevance of video games and gaming consoles to the higher and further education learning experience. April 2002. Techwatch Report TSW 02.01.

⁷³ Filipczak 1997 Training gets doomed. *Training*, August 1997, p.29.

⁷⁴ Filipczak 1997 Training gets doomed. *Training*, August 1997, p.31.

⁷⁵ Kirriemuir J (2002). The relevance of video games and gaming consoles to the higher and further education learning experience. April 2002. Techwatch Report TSW 02.01.

Criticism and Skeptics

Many argue that games in general do not teach in an effective way, and are a waste of time when compared to other methods of instruction. Stoll, for instance, is critical of “the obsession of turning the classroom into a funhouse,”⁷⁶ and argues that computers, or “teaching machines”

*...direct students away from reading, away from writing, away from scholarship. They dull questioning minds with graphical games where quick answers take the place of understanding, and the trivial is promoted as educational. They substitute quick answers and fast action for reflection and critical thinking [...] Turning learning into fun denigrates the most important things we can do in life: to learn and to teach. It cheapens both process and product: Dedicated teachers try to entertain, students expect to learn without working, and scholarship becomes a computer game.*⁷⁷

Mitchell and Savill-Smith⁷⁸ identify a number of possible negative impacts from (digital) game based learning, including: 1) health issues: headaches, fatigue, mood swings, repetitive strain injuries, etc., 2) psycho-social issues: depression, social isolation, less positive behavior towards society in general, increased gambling, substitute for social relationships, etc., and 3) the effects of violent computer games: aggressive behavior, negative personality development, etc. There are a number of studies that contradict the third assertion in particular, in fact a number of the paper cited do a pretty good job showing the lack of evidence for that assumption. Finally, still others point out that we know little about the impact of gameplay on the cognition of those who play them.⁷⁹ Emes⁸⁰ and Harris⁸¹ both put out literature reviews that no clear relationship between academic performance and the use of serious-games. However, between the two of them, they only considered five sources.

This wariness wasn't helped by terms like “edutainment” which referred to any kind of education that also entertains even though it is usually associated with video games with educational aims. The primary target group of this *fad* was preschool- and young children, focused on reading, mathematics, and science. The fad is considered to have failed because of “boring games and drill-and-kill learning.”⁸² It failed because the artifacts were inadequate, not because learning was not possible in this mode.

Finally, to end on an inconclusive note we point out that Susi et al conducted a survey of serious games in 2007 and concluded that “there is no conclusive answer to the question of evidence for the acclaimed

⁷⁶ Stoll, C. (1999) High-tech heretic: Reflections of a computer contrarian. New York: First Anchor Books p.13.

⁷⁷ Stoll, C. (1999) High-tech heretic: Reflections of a computer contrarian. New York: First Anchor Books p.13-14.

⁷⁸ Mitchell, A. & Savill-Smith, C. (2004) The use of computer and video games for learning: A review of the literature. Learning and Skills Development Agency. [www.LSDA.org.uk]

⁷⁹ Squire, K. (2002) Cultural framing of computer/video games. The International Journal of Computer Game Research, 2(1).

⁸⁰ Emes CE (1997). Is Mr Pac Man eating our children? A review of the impact of video games on children. Canadian Journal of Psychiatry, 42(4), 409–414. At www.cpa-apc.org/Publications/Archives/PDF/1997/May/EMES.pdf.

⁸¹ Harris J (2001). The effects of computer games on young children – a review of the research. RDS Occasional Paper No. 72. London: Research, Development and Statistics Directorate, Communications Development Unit, Home Office

⁸² van Eck, R. (2006) Digital game-based learning: It's not just the digital natives who are restless. EDUCAUSE review, march/april, 16-30.

benefits and potential consequences of games and game play.”⁸³ We have seen nothing more recent to counter this statement.

⁸³ Tarja Susi, Mikael Johannesson, Per Backlund, Serious Games – An Overview,

Appendix B: Stakeholder recruitment scripts

Recruitment Script for Initial Phone Contact

May I please speak with [Mr., Ms. Mrs. _____]?

My name is [research team member] and I am calling to see if you might be interested in coming to share your knowledge and expertise in a project being conducted by researchers at Sandia National Laboratories. The project is called the DISCERN project and involves developing interactive computer tools to assist in the management of water. You have been identified as a potential participant in this study because of your expertise and experience in [municipal] [agricultural] water use. The study involves creating a model of the Middle Rio Grande River Basin that incorporates both ecological and human factors that affect how water is used and managed. Ecological factors include things like water flows and relationships between the river, groundwater, and precipitation. Human factors include the political, economic, and cultural factors that influence how people use and manage water in the Basin. This study is attempting to develop a new kind of computer technology that accounts for both. The goal is to develop a tool that can be used for simulating what might happen to water resources in a watershed under different policy or regulatory scenarios. If successful, this technology may be used by water users, managers, and/or policy makers to support better water management and minimize conflicts between different users.

At this stage, the project is a computer modeling project in the early stages of development. It is being funded by Sandia Laboratories by an internal research and development grant. Computer modeling involves collecting data from the real world and translating it into mathematical relationships. The two kinds of modeling that this project involves are called “systems dynamic modeling” and “agent based modeling.” Systems dynamic modeling in the case of the Rio Grande Basin involves gathering information about how much water is in the river, how much it rains and snows, how much water we are taking out of the ground, and how all these processes affect each other. A model like this was built several years ago with stakeholders throughout the Basin. In this project we are incorporating that model with agent-based models. An “agent” as defined in this model is a certain kind of water user. By studying how a water user makes decisions regarding water use, we can create mathematical models that predict human behavior under different conditions. For the purposes of this initial experiment, we have chosen two types of agents to model: farmers and municipalities. We chose these two types of water users because their decisions have major impacts on water use in the Basin.

To build the agent models we are inviting [10 municipal] [20 agricultural] water users such as yourself to come spend two to two and a half hours at [location] on [date and time] to come share their thoughts and ideas about how the model might be improved to reflect more accurately how real water users make decisions. In the session there will be five to fifteen other participants sitting around a conference table using laptop computers set up in advance by the researchers. Two to five members of the project team will be present to facilitate the session and help out. You will be given a \$75 gift card from [TBD] for your participation on the day of the session.

At the session we will: (1) give an oral presentation about the project, (2) answer additional questions you may have about it, (3) go over a consent form regarding your participation which we will send to you beforehand by email/mail, (4) ask you to interact with the model through a simple computer interface which anyone can easily use, and (5) ask you questions about how it might be improved to more accurately reflect how you make decisions about water. The session will be in a relaxed environment where you may ask questions. You may choose at any time in the process not to participate or withdraw from the process. You will also be provided with contact information so that you can ask questions before and afterwards.

During the session, the computer you use will gather information about how you use the interface (what buttons you click and slider bars you move). That information will be used by the computer modelers to create generic agent models. No personal information of any kind will be collected through that process or link your identity to that data. After you use the computer, the project team will lead a group discussion where you will be asked your thoughts about how accurately the model reflected how you think about and make decisions regarding water. That discussion, with your permission, will be audio recorded so that we may take more accurate notes after the session. Once we have made those notes, we will destroy the recording. There are no identifiable risks to you participating in this study, outside of what you might expect sitting around a table having a discussion about water management. Any information we collect that may identify you as a participant (your name, contact info, etc.) will be kept separately from the information we gather through the study so that your participation remains confidential. No one besides the research team will have access to this information. Data collected through computer use and the group discussion will be used to improve the technology. The results of this data will appear in a report will file with Sandia Labs and may appear in scientific publications that result from the study. No personal identifying information of any kind will appear in any work product (report, paper, or presentation) from this project.

If you are interested in participating, we will send you a follow-up email/mail with more information including the time and location as well as a description and consent form explaining the study and your participation. If you agree to participate, we will call you in the days before the session to see if you have any further questions and remind you about the session.

At this time, do you have any questions? Do you think that you may be interested in participating? Is it ok if we send you additional information? Is it ok we contact you in a few days to see if you are interested and available to participate? Are there others who you think might be interested in participating in this project that you would be willing to share their contact information with us? If, so may we mention your name when we contact them?

Thanks so much for your time! We really appreciate it.

Email/Mail Follow Up

Re: Water Modeling Project

Dear _____,

I spoke with you on [date and time] about participating in the DISCERN water modeling project being conducted by Sandia National Laboratories. I am sending this email to follow up on our conversation and provide you with additional information.

We will be holding a session on [Day] [Date]] at [Time] at [Location]. The session will last approximately two hours. At the end of the session you will be given a \$75 gift card from [TBD] for your participation.

If you are interested in participating, we would like to confirm your space. We will call you in the coming days to do so. You may also email us at [email address] or call [person] at [number] to confirm.

Below is a description of the project, as I shared over the phone when we spoke. If after reading this, you have any questions or comments, please do not hesitate to email or call.

Thanks so much!

Project Description (included with email or letter):

The project is called the DISCERN project and involves developing tools to assist in the management of water. You have been identified as a potential participant in this study because of your expertise in water use as a/an water utility employee/agricultural water user. The study involves creating a model of the Rio Grande River Basin that incorporates both ecological and human factors that affect how water is used and managed. Ecological factors include things like water flows and relationships between the river, groundwater, and precipitation. Human factors include the political, economic, and cultural factors that influence how people use and manage water in the Basin. This study is attempting to develop a new kind of computer technology that accounts for both. The goal is to develop a tool that can be used for examining what might happen in a watershed under different scenarios. If successful, this technology may be used by water users, managers, and policy makers to support better water management and minimize conflicts between different users.

At this stage, the project is a computer modeling experiment in the early stages of development. It is being funded by Sandia Labs by an internal research and development grant. Computer modeling involves collecting data from the real world and translating it into mathematical relationships. The two kinds of modeling that this project involves are called “system dynamic modeling” and “agent based modeling.” System dynamic modeling in the case of the Rio Grande Basin involves gathering information about how much water is in the river, how much it rains and snows, how much water we are taking out of the ground, and how all these processes affect each other. A model like this was built several years ago with stakeholders throughout the Basin. In this project we are incorporating that

model with agent-based models. An “agent” as defined in this model is a certain kind of water user. By studying how a water user makes decisions regarding water use, we can create mathematical models that predict human behavior under different conditions. For the purposes of this initial experiment, we have chosen two types of agents to model: farmers and municipalities. We chose these two types of water users because their decisions have major impacts on water use in the Basin.

To build the agent models we are inviting 10/20 municipal/agricultural water users such as yourself to come spend two to two and a half hours at (location) on (date and time) to come share your thoughts and ideas about how the model might be improved to more accurately reflect how real water users make decisions. In the session there will be five to fifteen other participants sitting around a conference table with laptop computers. Three to five members of the project team will be present to facilitate the session and help out. You will be given a \$75 gift card from [TBD] for your participation on the day of the session.

At the session we will: (1) give an oral presentation about the project, (2) answer additional questions you may have about it, (3) go over a consent form regarding your participation which we will send to you beforehand by email/mail, (4) ask you to interact with the model through a simple computer interface which anyone can easily use, and (5) ask you questions about how it might be improved to more accurately reflect human decision making. The session will be in a relaxed environment where you may ask questions and choose at any time to not participate. You will also be provided with contact information so that you can ask questions before and afterwards.

During the session, the computer you use will gather information about how you use the interface (what buttons you click and slider bars you move). That information will be used by the computer modelers to create generic agent models. No personal information of any kind will be collected through that process or link your identity to that data. After you use the computer, the project team will lead a group discussion where you will be asked your thoughts about how accurately the model reflected how you think about and make decisions regarding water. That discussion, with your permission, will be audio recorded so that we may take more accurate notes after the session. Once we have made those notes, we will destroy the recording. There are no identifiable risks to you participating in this study, outside of what you might expect sitting around a table having a discussion about water management. Any information we collect that may identify you as a participant (your name, contact info, etc.) will be kept separately from the information we gather through the study so that your participation remains confidential. No one besides the research team will have access to this information. Data collected through computer use and the group discussion will be used to improve the technology. The results of this data will appear in a report will file with Sandia Labs and may appear in scientific publications that result from the study. No personal identifying information of any kind will appear in any work product (report, paper, or presentation) from this project.

If you are interested in participating, we will send you a follow-up email/mail with more information including the time and location as well as a description and consent form explaining the study and your participation. If you agree to participate, we will call you in the days before the session to see if you have any further questions and remind you about the session. Thank you!

Recruitment Confirmation Conversation (If needed)

May I please speak with [Mr., Ms. Mrs. _____]

Hi, this is [name]. We spoke and I sent you an email several days ago about the DISCERN water modeling project. I am calling to find out if you have decided to participate in the study. Do you have any additional questions or comments about the study or your participation at this time? Can we confirm your participation? Thanks so much!

Reminder Call

May I please speak with [Mr., Ms. Mrs. _____]

Hi, this is [name] of the DISCERN water modeling project being conducted by Sandia National Labs. This is just a reminder call about the session tomorrow at [time] at [place]. Do you have any questions or concerns? We'll see you there! Thanks so much for your time

Appendix C: Participant Instructions for Quantitative Data Collection

Login Instructions

Follow these instructions in the exact order they appear to start a simulation scenario.

1. Double click the mouse on the file: gov-sandia-discern-core.jar
2. In the Login Window click the circle next to “game_master”
3. Click the “Login” button
4. A new window will open. In this window click on “Scenario Filename” button
5. In the file window that opens double click on “LimitedDrought.csv” (do not close any windows).
6. Now go back to the Login Window and type the “participant code” you were assigned into the field that says “Name”
7. Click the circle next to “Municipal”
8. Click the “Login” button
9. A new window with the scenario should appear. If not start over.
10. When you are ready to start, go to the game master window and click the “start” button.
11. The scenario is now running. Make your decisions.

Important Notes:

- Do NOT close any windows or the scenario will end and you will have to start over and login again.
- If the scenario does not work, close a window and try the login again.
- Complete all three scenario files in the following order:
 - LimitedDrought.csv
 - IncreasingDroughtWithFlatMarket.cvs
 - CyclicDrought.csv
- To start a new scenario file, close a window and login again.

Simulation Instructions

Important! Make decisions ***exactly as you think you would in real life*** if you were presented with these scenarios. *It is critical to the accuracy of the model.*

Step 1: Fill out Participant Questionnaire STEP 1 (5 minutes)

Step 3: Practice scenario simulations (5 minutes)

- A. Login to computer simulation (see instructions above)
- B. Do a quick practice run of each of the three scenarios
- C. Experiment with the interface to get the hang of using the different tools and to try different options to see what happens. If a scenario stops or disappears login again.

Step 4: Run 3 scenario simulations (No more than 15 minutes per scenario)

- A. Fill out Participant Questionnaire STEP 2 while running scenarios
- B. Simulation Explanation:
 - 1. Each scenario has 10 rounds: each round = 1 year
 - 2. On the left side of the display are graphs and charts to help you make decisions about the water supply for your municipality.
 - 3. On the right side are slider bar tools and boxes for making decisions about water.
 - 4. To see the effects of your decisions, change the slider bars and boxes on the right. Press the “return” button on the keyboard to see how these decisions affect the displays on the left. To reset the displays to where they were at the beginning of the round press the “Reset” button.
 - 5. You can experiment as much as you want and try different combinations of decisions.
 - 6. Once you are ready to make your final decisions for that round:
 - A. Change the slider bars and boxes on the right to make your decisions.
 - B. Rank how politically risky you think these decisions are on a scale of 1 to 10 by moving the “Political Risk” slider bar. 10 is the most risky; 1 is the least.
 - C. Click the “Submit Decision” button.
 - 7. The computer will log your decisions for that round and then present you with new information.
 - 8. This will happen a total of 10 times.
 - 9. Once you have run through the entire scenario, close a window and start over with the next scenario file.
- C. Run all three scenario files completely through in the following order:
 - A. Run Scenario 1: LimitedDrought.csv
 - B. Run Scenario 2: IncreasingDroughtWithFlatMarket.csv
 - C. Run Scenario 3: CyclicDrought.csv
- D. Run each scenario file again as many times as you can in the remaining time.

Step 3: Fill out Participant Questionnaire STEP 3 (5 minutes)

Step 4: Reconvene for group discussion (25 minutes)

Appendix D: Modeling Water Rights in URGSiM

By : Jesse Roach (Sandia National Laboratories)

Initial Spatial Distribution of Water Rights

Because the MRG is not adjudicated, estimates of water rights are just that. URGSiM estimates of the quantity of water rights that might exist in the Middle Valley are based on irrigable areas for the most part, however more specific information is available in the case of Indian Water Rights. To allocate water rights in URGSiM, three water rights classes were defined: Indian Prior and Paramount (PP), Indian newly reclaimed lands (NRL), and non-Indian. Areas for the Indian water rights were obtained by personal communication with Chris Banet of the Bureau of Indian Affairs (April 11, 2011) and are shown in Table D.1 below. Indian Prior and Paramount rights are the most senior in the basin while Indian NRL rights were created more recently when drainage reclaimed lands previously not irrigable.

PUEBLO	Prior & Paramount	Newly Reclaimed	Total for Pueblo
Cochiti	821.8	1,053.975	1,875.775
Santo Domingo	1,745.7	2,555.020	4,300.720
San Felipe	1,426.3	2,404.230	3,830.530
Santa Ana	643.9	475.950	1,119.850
Sandia	740.2	2,682.340	3,422.540
Isleta	3,469.1	2,779.529	6,248.629
TOTAL	8,847.0	11,951.044	20,798.044

Table D.1: Indian water rights in acres of land for Prior and Paramount and Newly Reclaimed. The Prior and Paramount rights are the most senior in the basin with Newly Reclaimed having a much later priority.

The reaches in the MRG are Cochiti to San Felipe, San Felipe to Albuquerque, Albuquerque to Bernardo, Bernardo to San Acacia, and San Acacia to San Marcial. The Pueblo lands were assigned to the reaches as shown in **Error! Reference source not found. D.2**. The assumption of half San Felipe land in each reach is an initial guess that can be adjusted by the model user.

PUEBLO\REACH	Cochiti to San Felipe	San Felipe to Albuquerque	Albuquerque to Bernardo	Total
Cochiti	100%	0%	0%	100%
Santo Domingo	100%	0%	0%	100%
San Felipe	50%	50%	0%	100%
Santa Ana	0%	100%	0%	100%
Sandia	0%	100%	0%	100%
Isleta	0%	0%	100%	100%

Table D.2: Indian lands mapped to URGSiM river reach. The portion of San Felipe lands upstream and downstream of the pueblo is a user adjustable parameter with an initial guess of 50-50.

The non-Indian water rights were assigned based on a distribution of irrigable area for the Middle Rio Grande Conservancy District (MRGCD) reported in USACE et al 2002 page PHYMOD-65²³ and shown in Table D.3 below. The MRGCD Divisions are based on the location of major diversion structures, and thus do not necessarily correspond to the URGSiM river reaches which are based on stream gage locations.

Division	Total Irrigable Area [acres]
Cochiti Division	4593
Albuquerque Division	23456
Belen Division	37303
Socorro Division	14524
Total	79876

Table D.3: Irrigable lands in the Middle Rio Grande Conservancy District reported in the URGWOM model documentation (USACE et al 2002).

The MRGCD divisions are assigned to URGSiM Middle Valley reaches as shown in Table D.4 below. Based on a 1995 MRGCD GIS land-use coverage, an estimated 25 percent of irrigable lands in the Cochiti Division are below the San Felipe gage, and 46% of irrigable lands in the Albuquerque Division occur below the Central gage (USACE et al 2002, page PHYMOD-66-67)²³.

MRGCD Division	Cochiti Division	Albuquerque Division	Belen Division	Socorro Division
Middle Valley Reach				
Cochiti to San Felipe	75%			
San Felipe to Albuquerque	25%	54%		
Albuquerque to Bernardo		46%	100%	
Bernardo to San Acacia				
San Acacia to San Marcial				100%
Total	100%	100%	100%	100%

Table D.4: The relationship between MRGCD division (defined by locations of major diversion structures) and URGSiM reaches (defined by river gage locations) in terms of irrigable area.

The La Joya ditch between Bernardo and San Acacia, which is not formally part of the MRGCD includes approximately 250 acres of irrigable land (USACE et al 2002, page 71)²³, and the Jemez river (also not part of the MRGCD) includes 5371 acres of irrigated agriculture.⁸⁴

From the information in Table D.1 through Table D.4 above, we have an estimate of irrigable area by middle valley reach, actual irrigated area for the Jemez reach, and quantified Indian water rights by reach. URGSiM uses this information to calculate the maximum irrigable area available for non-Indian use as the irrigable area less the total Indian water rights in each reach. Finally, because water rights can be lost with extended non-use, available water rights are probably more closely tied to actual irrigated area than irrigable area. In the Middle Valley historical estimates of actual irrigated area served by the MRGCD are in the range of 50,000 to 60,000 acres, or about 2/3^{rds} of the 80,000 acres irrigable. Thus, URGSiM assumes that 2/3^{rds} (user adjustable parameter) of irrigable acres in the Middle Valley will have a water right. As a result of these calculations, URGSiM assigns the initial spatial distribution of water rights in the Middle Valley shown in Table D.5 below.

Reach	Prior and Paramount	Newly Reclaimed	Non-Indian	All
Cochiti to San Felipe	3281	4811	0	8092
Jemez River	0	0	5371	5371
San Felipe to Albuquerque	2097	4360	2660	9118
Albuquerque to Bernardo	3469	2780	25493	31741
Bernardo to San Acacia	0	0	165	165
San Acacia to San Marcial	0	0	9586	9586
Total	8847	11951	43274	64072

Table D.5: Initial Spatial Distribution of Surface Water Rights in URGSiM.

Initial Temporal Distribution of Water Rights

Agricultural water rights are defined by an area and a priority year. The area defines the quantity of the right while the priority year defines the quality of the right. The older the priority year the more senior is the right. As with the area associated with the water rights, there is more certainty regarding the priority of Indian rights than non-Indian rights. Prior and Paramount are the most senior rights in the Middle Valley, and URGSiM assigns a priority date of 1540 to all Prior and Paramount rights. This date is somewhat arbitrary, but is the year of Spanish contact with the Pueblos, and so is older than any possible Spanish water right. URGSiM assigns a priority year of 1930 to all Newly Reclaimed lands as this is the date of the water right application by the MRGCD for rights associated with newly created

⁸⁴ McAda, D. P., and P. Barroll, 2002, *Simulation of Ground-Water Flow in the Middle Rio Grande Basin Between Cochiti and San Acacia, New Mexico*. U.S. Geological Survey Water-Resources Investigations Report 02-4200, Albuquerque, New Mexico.

irrigable lands expected to be made available through drainage projects.⁸⁵ Finally, non-Indian rights for a given reach are split and distributed uniformly from 1850 to 1950. Thus, for example, the San Felipe to Albuquerque river reach has 2097 acres of Prior and Paramount rights with a priority year of 1540, 4360 acres of Newly Reclaimed rights priority rights with a 1930 priority year, and 2660 acres of Non-Indian water rights which are split into 101 26.34 acre rights for each year from 1850 to 1950 inclusive. This is highly arbitrary and certainly wrong, but set up to get the model running. Better information on the distribution of priority years associated with Middle Valley water rights can be added as it becomes available.

Pumping Impacts on Surface Water Flows

The rapid growth of groundwater pumping by municipal areas especially Albuquerque and Rio Rancho in the twentieth century has led to cones of depression that increase the rate of river leakage near these cities. Thus groundwater pumping is decreasing surface water flow and thus impacting more senior water right holders. To address this issue, the State of New Mexico requires that some portion of groundwater pumping be offset by surface water rights. The amount of offset is determined by the State either by an equation known as the Glover-Balmer equation, or by a regional groundwater model run with and without the pumping in question. To estimate Albuquerque Groundwater Basin pumping impacts on river flows in URGSiM, a baseline run from 2010 to 2110 was run, and then repeated 51 times (once for each zone in the URGSiM Albuquerque Groundwater Basin model) with 5 cubic feet per second (cfs) of additional pumping to a given groundwater zone for the first month only. The change in total surface water flow past San Acacia was then compared to the base run to estimate the temporal distribution of that 5 cfs of pumping in a given zone on surface water flows at San Acacia. These responses are shown cumulatively as a function of the extra volume pumped in Figure D.1 below. For clarity, only zones 1-10, corresponding to the Cochiti to San Felipe reach are shown. Figure D.2 shows the location of these groundwater zones in the URGSiM model. For more information on the URGSiM groundwater model of the Albuquerque Basin, see Roach and Tidwell 2009.⁸⁶

As can be seen in Figure D.1 with reference to Figure D.2, both the speed of response and the total response to pumping are impacted by the location of that pumping. Pumping close to the river such as in Zones 2 and 3 (Zone 1 is below Cochiti reservoir and acts differently) has an almost immediate impact, and a cumulative impact of 100% meaning all pumping there is “paid” by the river. Pumping from zones further from the river (e.g. Zones 8-10) has a delayed impact, and plateaus at far less than 100% meaning pumping from these zones does not impact the river as significantly, even in the long run. For modeling flexibility, the response functions were normalized so that all end at 100%, and then the fraction of pumping eventually “paid” by the river (100% for Zones 2 and 3 above, 39% for Zone 10 above) is stored as a separate variable. In this way the model user can adjust the estimated total impact and have the timing of that impact determined by the response function. These normalized response functions and the fraction eventually paid were implemented in URGSiM such that every year the total groundwater pumping from a given zone is tracked and the total impact on the river as a result of that pumping estimated.

⁸⁵ SS PAPANOPULOS & ASSOCIATES, INC. 2002, Evaluation of the Middle Rio Grande Conservancy District Irrigation System and Measurement Program, December 2002 <http://www.ose.state.nm.us/water-info/MRGCD-efficiency/index.html>

⁸⁶ Roach, J. and Tidwell, V. 2009, A Compartmental–Spatial System Dynamics Approach to Ground Water Modeling. *Ground Water*, 47: 686–698

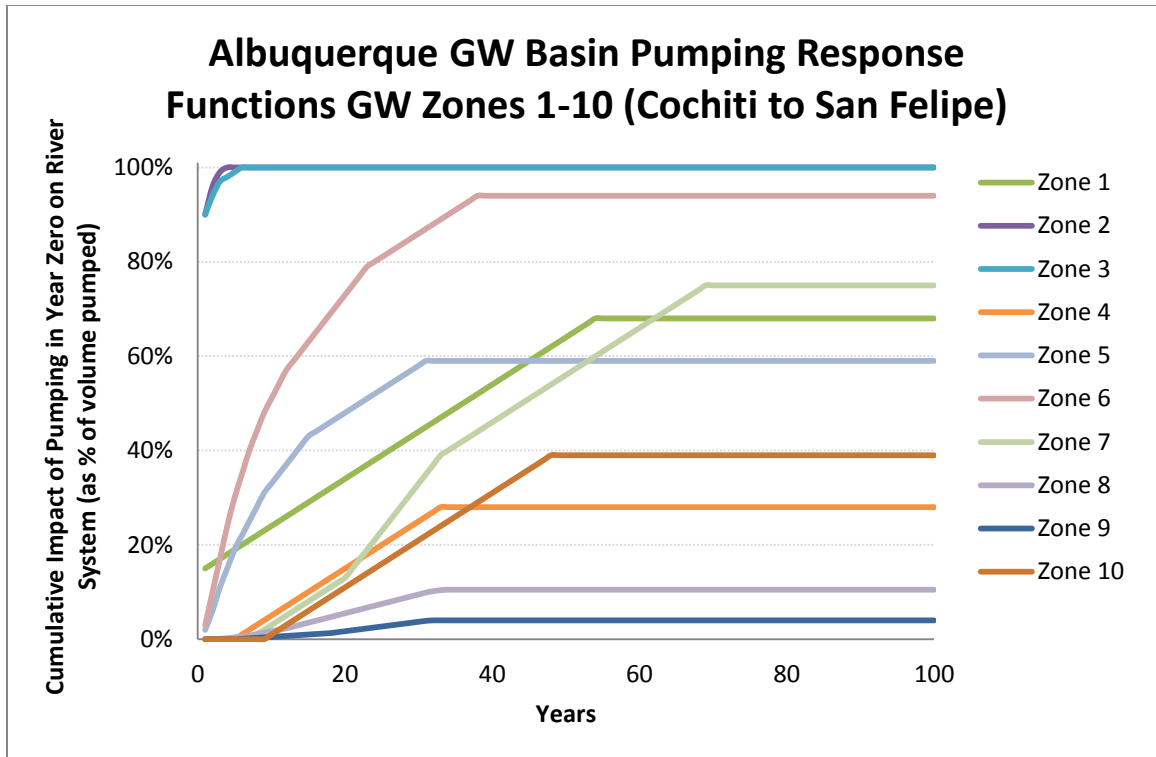


Figure D.1: Cumulative groundwater pumping response functions for pumping in year one of the Albuquerque Groundwater Basin impact on total water flow past San Acacia as a percentage of the pumping. Only 8 of 51 zones are shown to avoid clutter.

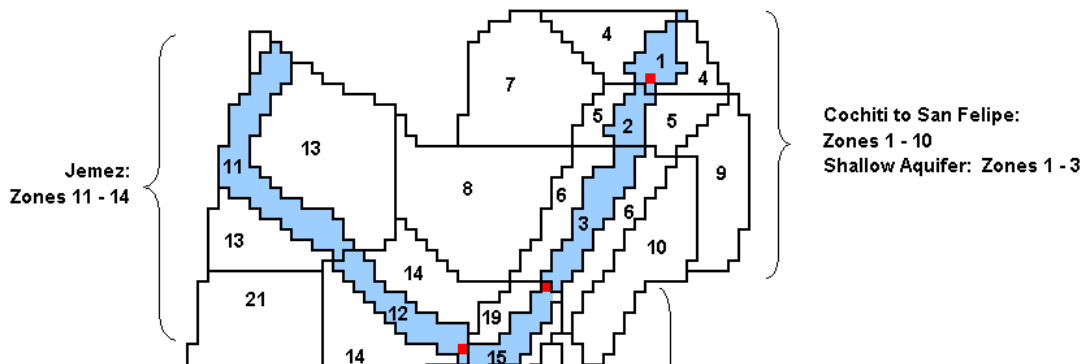


Figure D.2: The configuration and numbering of northern groundwater zones in the URGSiM groundwater model of the Albuquerque Groundwater basin. For more information see Roach and Tidwell 2009.

Legal Pumping Offset Requirements

While groundwater pumping has a delayed and negative impact on surface water flows due to increased river leakage or interception of water that would otherwise end up in the river, it can also have an almost immediate positive impact on surface water via return flows. For example, a municipal well at some distance from the river that pumps groundwater may impact river leakage for years to come, however if the water is used, then treated, and then returned to the river, in the short term the river may have more flow than it would have without the pumping and associated return flows. Thus, typical

groundwater use by a municipality will result in excess water in the river in the short term and reduced water once the pumping and return flows stop, or once the pumping induced leakage from long periods of pumping exceeds the return flows from a given year. As a result, return flows are considered credits that can be applied towards the pumping induced leakage impacts in the same year (i.e. “surplus” return flow credits cannot be stored for use the next year). The legal pumping offset requirement for a given year will be the difference between pumping impacts on the river that year (resulting from years of pumping) and return flows that year. If return flows exceed pumping impacts, there will not be an offset requirement.

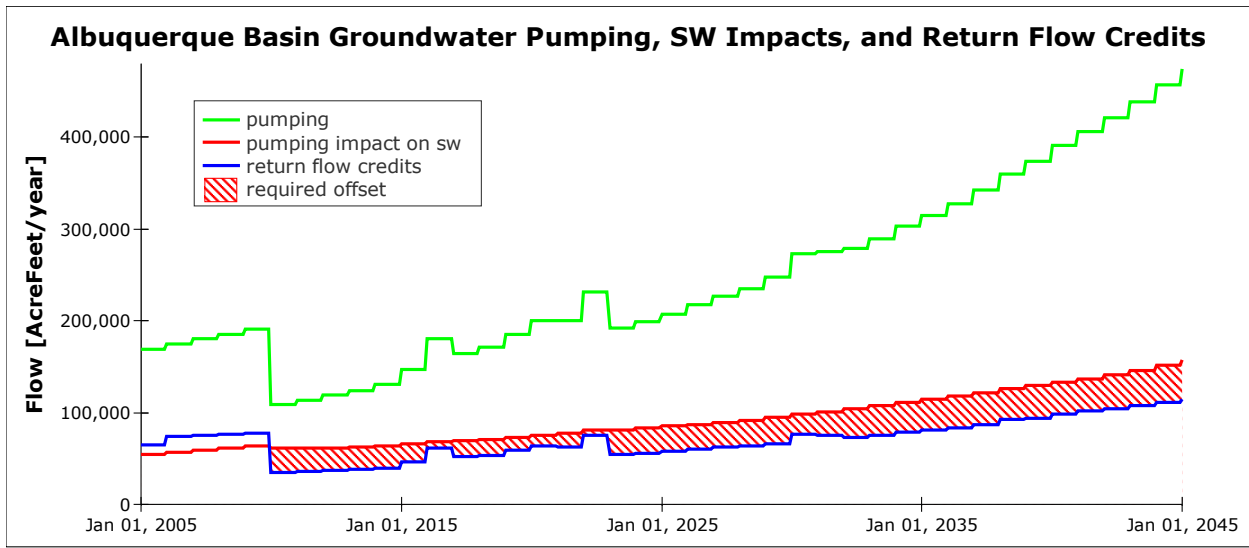


Figure D.3: Groundwater pumping, groundwater pumping impacts on the surface water system, groundwater return flows, and the resulting net impact of pumping that requires offset.

Rights Necessary to Offset

By estimating pumping impacts through time, and tracking return flows, URGSiM can estimate if additional surface water rights are necessary to support groundwater pumping. **Error! Reference source not found.** shows an URGSiM⁸⁷ run where pumping, resulting impacts on the surface water system, and return flow credits are all tracked. The hashed area, which is zero as long as return flows are greater than pumping impacts, represents the volume of water due the surface water system that must be obtained by transferring surface water rights to a groundwater point of diversion.

Surface Water Rights Used to Offset Pumping Impacts

Once the offset requirement is known, URGSiM checks to see if that volume of water can be met by San Juan – Chama water rights owned by the pumper under obligation. If they can, there are no water rights transferred. However, once San Juan Chama rights are not sufficient, or are being used for another purpose (e.g. direct diversion and consumption), a water rights transfer is requested. If the model user has elected to allow water rights transfers (via a check button), URGSiM will initiate a transfer. To account for the fact that not all water rights will be for sale, URGSiM randomly blocks some subset of all agricultural water rights from transfer. Currently, 100% of Prior and Paramount and Newly Reclaimed

⁸⁷ URGSiM.10.03.2011.sip

Indian rights and 90% of Non-Indian rights are blocked from transfer. URGSiM looks at the water rights transfer amount, and the water rights available for transfer from oldest to newest priority year and retires all available water rights of a given priority year until enough have been retired to satisfy the water rights transfer request. As seen in Figure E.4 **Error! Reference source not found.** below, approximately 20,000 acres of agriculture are retired by URGSiM by 2045 under default assumptions.

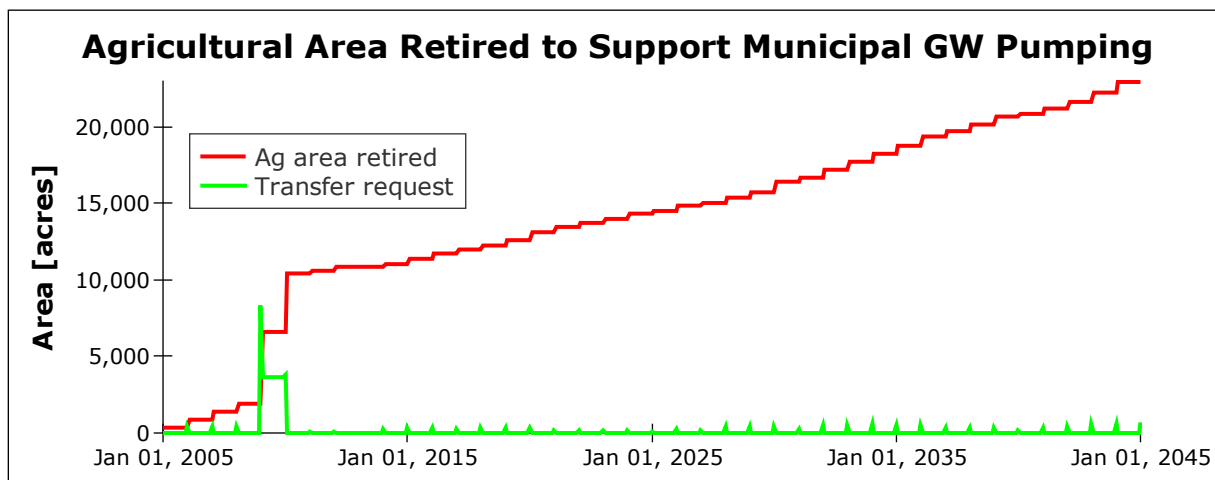


Figure D.4: Agricultural area retired through time by URGSiM to support the groundwater pumping shown in **Error! Reference source not found.**

Next Steps

This document outlines the basic structure set up in URGSiM to account for water rights and track groundwater pumping impacts on the surface water system. The largest piece still missing from a conceptual standpoint, is the management of the system from a priority administration perspective. So while the current setup retires agriculture lands for municipal groundwater use, in years of shortage everyone shares in the shortage equally on the surface water side, and municipalities pump whatever they want from the ground. Under a priority doctrine management scheme, the model would evaluate available water supply at each time step, and match demand by the most senior users to that supply. This would impact reservoir operation as storage rights are junior to most agricultural rights. It would also require rules to handle situations where municipalities which might be relatively junior users, but whose demand is quite firm would be cut-off by priority administration.

Next, it would be worth spending more time developing the response functions, or looking at other ways to estimate pumping induced impacts on the river system, especially non-linear responses, or binary approaches where the system is treated differently when the river is “connected” to the aquifer as compared to when it is perched above the water table. Perhaps most importantly however, the implementation described here is a working framework that suffers most significantly from lack of good data. The specific data gaps that are tractable are

- The portion of San Felipe Pueblo PP and NR lands that are upstream of the San Felipe gage cross section.
- The agricultural water rights that have already been purchased by municipalities to offset groundwater pumping impacts.

- The agricultural consumptive use right. This connects area to water right and is currently set at 3 feet in URGSiM.

The data gaps that are less tractable are

- The amount of Non-Indian water rights available in the Middle Valley and the priority dates associated with them.
- The percent of total water rights that will be available for purchase at any given time. This involves incorporation of a water market model.

The implicit policy of retiring agricultural lands to support municipal growth is one of the dominant themes in the Middle Valley from a long term planning perspective. Because of the complexity of the issue, it has not been adequately captured in simulation models of the basin to this point. This effort is a first attempt to begin to remedy that situation.

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