Agent-Based Models of Socio-Hydrological Systems for Exploring the Institutional Dynamics of Water Resources Conflict

by

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ABSTRACT

The Basins-At-Risk theory formulates relations between institutional capacity in a basin and the level of water conflict in that basin, suggesting that higher levels of institutional capacity will lead to reduced levels of water conflict in a given system. I test the substance of this theory using comparative, simulation-based analysis of water resources systems in the USA and Spain. I determine whether, given two artificial societies experiencing water conflict, expanding institutional capacity would indeed lead to reduced conflict levels. I develop and apply two agent-based models of society and hydrology: one for Albacete, Spain, and the other for the Snake River, eastern Idaho, USA. Each model incorporates essential elements of the regional society: real world actors are translated into proactive deliberative agents using a BDI framework; the hydrology/geology is represented either through use of pre-existing models, or basic hydrologic simulation; economic, societal and other dynamics are represented through additional databases and agent rule bases. I apply the models experimentally to explore the societal effects of adding an additional institution to the existing water resources management institutions: ground water banking, a new set of rules for agents to interact with their hydrologic system. I run both models over historical and projected time periods, testing out different scenarios of variation in internal and external agent environment to explore the detailed dynamics of each system. Results and analysis suggest that institutional capacity and water conflict dynamics are strongly related, but that the direction of influence can vary. I identify critical elements of the design of ground water banking institutions, when considering their potential success in mitigating conflict. I also investigate the possibilities of engineering a universally portable socio-hydrologic agent, and discover that while the concepts of the chosen cognitive architecture may be portable, it is effectively impossible to guarantee a fully portable technical implementation.

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1.0 ... Introduction

1.1 ... Institutional analysis and water conflict

A recent prominent theme in water resources management research (e.g. Wolf 1997, Wolf 1998, Beach et al 2000, Carius et al 2006) has been the statistical and qualitative study of international water systems for the purposes of determining those conditions that lead to conflict and those that avoided or mitigated conflict. One of the findings suggests that fostering and maintaining appropriate institutional capacity is critically important to reducing the likelihood of conflict. As Carius et al (2006) suggest, “the key variable is not absolute water scarcity, but the resilience of the institutions that manage water and its associated tensions” (Carius et al 2006: 1). Miller et al (1997) suggest that water allocation institutions have a critical role to play in mitigating conflict over water allocation due to climate change. This finding is not restricted to academia. The Development Assistance Committee of the OECD recently released a report suggesting that “the development of shared data, information systems, water management institutions, and legal frameworks helps to sustain efforts to reduce the risk of conflict” (OECD 2005).

1.2 ... The influence of institutions on domestic conflict

The focus on international water conflict in the research community is perhaps understandable: international conflicts seem more serious from the perspective of potential armed escalation, even though several studies have pointed out that water wars are extremely rare and international water conflict seems more a driver for cooperation than antagonism: “water is a trigger for conflict, but a reason to make peace” (Ohlsson 1997:13). The domestic context of links between institutional capacity and conflict has seen far less attention outside of research focusing on the developing world (e.g. Hamdy et al 2002). Work has mainly focused on the details of implementing or evaluating water trading institutions (Easter et al 1999), tracking institutional change in response to climatic and economic forcers (Miller et al 1996; Livingston 1994), or exploring the role of institutions in integrated water resources management (Solanes and Gonzalez-Villareal 1999): in other words, how to design better institutions, and how institutions are changing in response to social, economic and environmental shifts. Very little work has been done explicitly exploring the effect of different forms and degrees of institutional capacity, and changes to institutional capacity, on water conflict. It is unclear why this is so. Domestic conflicts may represent much more complex and nuanced cases than international settings, or may simply be less high profile and so less attractive for researchers (or for funders). However, water conflict in the developed world appears to be more intractable at a domestic scale, far less an occasion for cooperation than in international settings (Ohlsson 1997). This may be due to their lower profile (high profile international disputes tend to attract resources for their resolution), or because the complexity of the interaction between management entities can be much more complex for local and regional water resources. In any case, institutions on a domestic scale are likely to be as important as their international counterparts: many countries have evolved complex vertically and horizontally distributed institutional structures for water resources management that are implicated in every aspect of the management and use of water, from bore-hole to tap and back again. *The relations between these institutions and the water conflicts their host systems often experience form the general focus area of this thesis*.

This paper seeks to direct more attention to the relations between institutional capacity and domestic conflict, using a comparative, simulation-based analysis of regions in the USA and Spain. The USA and Spain are chosen on the basis of several important characteristics: the existence of a number of serious domestic (inter- and intrastate) water conflicts that threaten the social, economic and environmental fabric of entire regions, providing a number of options for case selection; the relative abundance of information on the evolution of these conflicts and associated institutions, making for more easier calibration, verification and validation of conflict models; and the sophistication of pre-existing tools for tracking and modeling the physical basis of such conflicts, allowing the conjunctive analysis of social, economic *and* environmental systems related to conflict. Of course, the settings are not identical in these respects: data on land and water use is better organized and more accessible in the US compared with Spain; Spain has a very different political and institutional structure for managing water and water conflicts compared with the US. This is why a comparative analytical approach is adopted: by comparing simulations of these different settings, the dynamics of each system can be put in context, and some useful side lessons obtained as to the viability and universality of using agent-based approaches to simulate water conflict settings.

1.3 ... Institutions and water conflict in the western US

In the United States, real or potential water conflict is most acute in the western states, where it represents a serious challenge to regional social, economic and environmental health. Fundamental ecohydrological realities – low precipitation and low river density – have contributed to setting up western American society and economy for conflict. But most of the problem is sourced in social, economic and institutional trends: growing cities, a huge industrialized irrigated agricultural base, and a historical record of local, state and federal institutions adopting a development-against-all-odds approach to meet profligate demand absolutely disconnected from hydrological and climatological realities (Reisner 1987). One response to such realities is new construction of water resource infrastructure: augmenting dam or canal capacity, tapping new underground storage, or altering the flows of water around storage and distribution systems. But even changes to physical infrastructure may require institutional intervention, such as changes to dam operation policy or the structure of allocation agreements. Furthermore, any changes to physical infrastructure immediately come up against a variety of major local, regional and national institutions. From state water law and local groundwater users associations, to interstate compacts and state water resources management agencies, to national Acts of Congress and major federal bureaucracies, institutions of one form or another are likely to present barriers or bridges to change in western American water resources management. As Livingston (1994) suggests, "Institutional arrangements set the ground rules for resource use. At best, institutions facilitate achievement of economic and social goals. At worst, they establish impediments to efficient resource use" (Livingston 1994: 1), as well as possibly causing environmental damage, social conflict and promoting unsustainable water resources management.

1.4 ... Institutions and water conflict in eastern Spain

Conflict over water in Spain is nothing new, and nor are water institutions. The country has severe disparities in the distribution of water by volume: the northern basins of Spain receive 18 times more water than the arid southeastern basins (Garrido 2001). When paired with the economic and demographic realities of growth in the southern Mediterranean climates of the country, conflicts appear inevitable. This is particularly true when we consider that, like the US, Spain devotes over 80% of its water to agricultural irrigation (*ibid*). Consequently, the bulk of the institutional capacity in the country is organized around the task of obtaining water for and distributing water to the agricultural community.

Like the western US, Spain has an abundance of water institutions, although some of them are far older than their western US counterparts: water courts were operating in Spain from the late middle ages (Maas and Anderson 1978). Johansson et al (2002) suggest that in Spain as much as elsewhere, "the laws and rules that define water distribution will naturally affect the performance of the system" (Johansson et al 2002, 187). Swyngedouw (1999) argues that "throughout this [20th] century, water politics, economics, culture and engineering have infused and embodied the myriad tensions and conflicts that drove and still drive Spanish society" (Swyngedouw 1999, 1). More recently, the National Water Plan (NWP) of 1993, which proposed an ambitious set of new storage and distribution infrastructure projects, generated significant political conflict between the various autonomous regions of Spain and the central government (Sauri and del Moral 2001). Water institutions in Spain appear to be shifting away from the classic approach of the 'hydraulic age': building their way out of trouble with dams, pipelines and other storage and diversion infrastructure. After the problematic reception of the NWP, the Spanish federal government engineered a radical shift in policy, now "recognizing economic costs and environmental concerns" (Bukowski 2007, 2). Recent work by Gomez-Limon and Martinez (2005) suggests that the importance of water markets (as an economic institution to supplement existing institutions) has been underestimated in Spain; they recommend the implementation of irrigation water markets in the Duero Basin of northern Spain as a way to "increase economic efficiency and agricultural labor demand, particularly during droughts" (Gomez-Limon and Martinez 2004, 1). Albiac et al (2003) make a detailed study of a more traditional approach to water scarcity, physical transfer of water from one region to another. In this case, the water transfer is taking place between the Ebro basin and several south-eastern regions of Spain. These authors take an institutional perspective, exploring the economic costs of the water transfer, and suggesting that the physical solution falls short of being truly sustainable. They recommend instead that the transfer be accompanied by demand management - an institutional solution - to mitigate its lack of economic sustainability (Albiac et al 2003).

Despite the increasing realization in Spanish water management agencies as well as academia of the conceptual and practical linkages between socioeconomic institutions and the availability of water for human use, the Spanish national press continues to be replete with stories of political conflict between farmers in different regions, between farmers and cities, between cities, between regions, and between regions and the national government (Llamas 1988; Swyngedou 1999). Garrido (2001) suggests that the root of the conflict is the "growth in water demand and maturity of the Spanish water economy" (Garrido 2001, 237). While Garrido appears to be suggesting that practical realities of social and economic growth are responsible for conflict, this thesis will argue (adopting the approach pioneered by the Basins At Risk (BAR) project at Oregon State University; OSU 2003) that it is institutional capacity which is fundamentally to blame for conflicted water use and management. It is, in any case, abundantly clear in Spain that institutions as well as infrastructure and climate play a critical role in the existence and severity of conflict: national and regional plans compete for legislative and fiscal attention; federal agencies compete with regional, local and now supranational agencies (the EU Water Framework Directive) for jurisdiction and control. In some ways, the climatic and hydrologic setting is on the simple side of the equation; the number and diversity of competing institutions and philosophies regarding water management in Spain adds huge complexity and uncertainty to the picture. As Cots et al (2007) suggest, "current European water assessment and management systems are increasingly under pressure to develop new practices capable to meet growing societal demands for sustainable development as well as mounting biophysical pressures such as climate change" (Cots et al 2007, 2). Note that the problem is largely conceptualized as a societal problem requiring changes in practice, in other words, modifications to existing institutions: "Moving towards a more flexible and adaptive paradigm capable to deal with uncertainty, multiple perspectives... will require a shift in the design of institutions" (*ibid*, 3). It is a short conceptual leap from there to the idea that not only is existing institutional complexity linked to problematic water management, but that a lack of capacity for institutional change may have similarly dire implications for conflict.

These brief introductions to both Spanish and US settings are intended to highlight the importance of institutions to water management and conflict. As such, they ground a core proposition of the thesis: *if we are to efficiently and effectively engineer new institutions or alter existing ones, we need to understand the influence of different forms and degrees of institutional capacity on the generation and/or resolution of conflict in the domestic setting*. Achieving this understanding could be approached from a number of angles; this thesis proposes the use of systems modeling to obtain simulation-based evidence of a qualitative and theoretical relationship between particular forms and degrees of institutional capacity, and the generation or resolution of water conflict.

1.5 ... Justification for focus area selection

The choice for the first focus area, the state of Idaho in the western US, is mainly due to the fact that the state is broadly representative of the emerging social, economic and environmental character of a new American West: increasing and increasingly urban populations (IDCL 2005), a rapidly growing economy (Thredgold 2006; IDCL 2006) and an agricultural sector (dependent largely on irrigation) seeing a trend towards fewer, larger and more industrialized farms (IRP 2006). Most major rivers in the state are over-appropriated, and conflicts of varying severity are emerging throughout the state. As for many states in the West, these appear to stem from fundamental collisions in use at the nexus of multiple interests and value systems: preservation of endangered species under the auspices of the ESA, growing urban demand, Native American assertion of senior water rights, and traditional agricultural hegemony over water rights and usage: "demand for water by existing agricultural and urban users outstrips available supplies in many cases…so demand for water for public purposes or for increased urban supplies necessarily conflicts with existing patterns of water use" (Weinberg 1997: 5). As climate change looms, two significant shifts in Idaho's hydroclimatological character suggest serious potential future conflict within the state: increased summer temperatures and reduced summer rainfall, increased winter runoff but reduced winter snow-pack (Hamlet and Lettenmaier 1999). Potential increases summer temperatures and reductions in summer rainfall would lead to reductions in natural flows at the most critical time for agricultural users; the potential reduction in winter snow-pack would lead to less spring and early summer runoff, further decrementing natural flows and groundwater recharge. Meanwhile, increased winter runoff would lead to elevated natural flows at entirely the wrong time of year for the agricultural growing season. Options to adapt to and mitigate the effects of these climatic shifts include changes to the physical infrastructure of water abstraction, storage and distribution, and/or changes to the institutional structure by which water is managed in the state. Coupled with the potential for a narrowing in the hydrological capacity of the system, new uses and users are coming online that threaten to complicate and further stress the system: Concentrated Animal Feeding Operations (CAFOs), dairies, municipalities, aquaculture, power, traditional irrigated agriculture, in-stream flow allocation for environmental use, and recreational users are coming into legal and political conflict over the management of the system. Some conflicts are emerging, ironically, through the efforts of some users to become more efficient. As the canal companies line their canals and convert to sprinkler operations, less water infiltrates the aquifer, with concomitant effects on the aquifer phreatic surface. This may be causing reductions in spring flows downstream upon which other users depend. Layered on top of these biophysical, demographic and economic realities is an archaic system of water rights based on the doctrine of prior appropriation. This doctrine dates back to a period prior to the emergence of powerful centrifugal pumps after WWII, and so is ill-equipped to handle ground water pumping at an institutional level, and certainly not in a conjunctive manner with surface water resources. Consequently, the current water rights system in Idaho is under full review by the state department of water resources. This implies significant institutional uncertainty that is arguably contributing to the genesis and prolongation of conflicts. This institutional uncertainty is compounded by an ongoing lawsuit at the state supreme court, brought by a consortium of surface water users against ground water users in the basin. Clearly, the current legal, political, social, economic and hydrologic complexities of water conflict in Idaho provide an ideal point of departure for an effort focused on exploring the generation and/or resolution of conflict due to changes in institutional capacity.

Time and resource limitations of this project mean a focus on a sub regional conflict emerging in eastern Idaho over surface and groundwater use around the Eastern Snake Plain Aquifer (ESPA) and the Snake River. In addition to the complex and lengthy process of water rights adjudication (IDWR 2006) being conducted by Idaho Department of Water Resources (IDWR), the Idaho Water Resource Board (IWRB) is currently working with private consultants, state and federal agencies to develop a range of options for better management of a scarce resource and resolve outstanding legal challenges. Options being considered include groundwater banking (Schmidt 2006), new water transfer regulations and expansion to surface storage: a range of physical and institutional enhancements to the existing system. The ESPA social-biophysical system is at a critical juncture for resource management: conflict is already emerging, and forecasted climatic, population and economic changes that may enhance the conflict makes for some urgency in the search for solutions.

This specific focus area was selected on the basis of several additional factors: first, there is currently an active conversation among stakeholders in Idaho over potential institutional alternatives – groundwater banking being prominent among them. Consequently, detailed information on potential groundwater banking implementation options in Idaho already exists (e.g. USBR/IWRRI 1999; Contor and Johnson 2005) as well as ongoing research by IWRRI and USBR into the substance of alternative options (USBR/IWRRI 2006). This provides a rich, readily available source of data for developing, parameterizing and having expert review of simulation scenarios. Second, any simulation of a water resources system would be deficient if it did not actually incorporate some hydrological modeling. A sophisticated, robust groundwater modeling tool already exists, the IDWR/UI Eastern Snake Plain Aquifer Model (ESPAM: Cosgrove et al 1999). This is a 2D finite difference model based on the respected MODFLOW code from the USGS, and simulates the flow of surface and subsurface groundwater in the ESPA area. The beta version of the model, the results of which this paper is written on, did not link directly with this model (although this is a planned development in coming months). However, its simple hydrological module draws on the principles of the ESPAM and uses the same time series calibration data, so does have some hydrologic functionality. Thirdly, the conflict of interests and values in the ESPA area bears strong similarities to other settings in the Western US. Analytical conclusions from modeling this system may consequently hold significant external validity.

The second focus area in eastern Spain was initially chosen, rather prosaically, because of some of the author's work on a separate project related to the Albacete municipality in Castilla-La Mancha. The striking similarities, and yet stark differences, between the eastern Spanish and western American contexts suggested some fruitful comparative work could be undertaken. On closer inspection, it became even clearer that the setting in Albacete provided some rich material for simulation and analysis. The Albacete municipality and provincial region is an exceptionally arid area, receiving less than 8 inches of precipitation a year. Climate change threatens to diminish this even further as the century unfolds. The existing surface water resources - the Jucar River and associated tributaries - are heavily over abstracted, to the point of zero surface flow through much of the region. Extensive agricultural development, which began in the region around the city of Albacete in the late 1950s (Angelo, pers. comm. 2007), has largely tapped into the Eastern Oriental aquifer and caused extensive and severe drawdown (Lopez Sanz 1999). The ground water system remains around 30% over-abstracted each year (i.e. pumping is at least 130% of recharge to the aquifer in any given year; Angelo, pers. comm. 2007), and the water table has dropped to the point where pumping costs and water quality concerns are serious considerations both for farmers and the local urban communities. As Carmona and Varela-Ortega (2007) point out, the region has suffered from historical policies encouraging ground water use for agricultural irrigation irrespective of its fundamental hydrologic sustainability - first the Franco government, and then the European Union (Carmona and Varela-Ortega 2007; Varela et al 1998). ,

Spain differs considerably from the western United States in its institutional setting. While Western US water law was originally based on Spanish legal precedent, subsequent institutional modifications have caused some divergence. California and many of the wetter states in the West, for example, evolved a complex part-riparian, part-appropriative system (Kanazawa 1998). But even among the drier states such as Colorado, the prior appropriations system that had spread across the region and originates in Spanish water law underwent considerable modification. This is above and beyond the fact that the prior appropriations doctrine emerged more as a practical response to the demands of mining with limited water in the 1800s, rather than as a simple facsimile of the colonial, Hispanic institutions (*ibid*). With the emergence of the EU Water Framework Directive (WFD) as a new and powerful force shaping European water resources management Chave 2001), Spain pulls well away from the Western US model which has nothing like the level of federal attention to local detail that the WFD implies. As Chave suggests, the WFD is “probably the most significant legislative instrument in the water field to be introduced on an international basis for many years” (Chave 2001, 1). Among the key philosophical principles of the policy are elements that are generally inimical to the common conception of Western US water law and policy: the precautionary principle, an explicitly selected high level of protection, deliberate steps to take preventative action, forcing the polluter pays principle on industry, and integrating WRM into other environmental policies (*ibid*). Like all parties to the EU, Spain has being going through steps outlined in the WFD text: classification of hydrological systems into River Basin Districts, development of reference condition data, assessment of ecological status, and so on, with the ultimate objective being to achieve “good status” for all European waters including those in the Spanish peninsula (Borja et al, 2004). What this means for an irrigator, the central ‘agent’ in the water systems of both the Western US and Spain, is unclear. Recent work by Bazzani et al (2005) suggests that the directive in some regions “may be summed up in a minor reduction of water use associated with a sharp decrease of farm income and a significant reduction of employment” (Bazzani et al 2005, 1). The same authors, however, point out that the effects of such a large and complex institution on such a large and complex system as European water resources are likely to be specific to locale.

What is clear is that Spanish institutions are different from Western US institutions, particular with regard to governmental interference in the day to day business of providing and making use of water supplies by agriculture. That is not to say that the two systems do not have anything in common: both settings are heavily dominated in terms of water use by their agricultural systems; subsidies are a powerful driver to agricultural production; and the water systems in both regions are near exhaustively engineered. However, the subtle differences in the reach and power of the institutions in each setting makes a comparison worthwhile, as well as the potential differences in the way that individuals will interface with those institutions. In some ways, the Spanish setting is more fertile for a study of this sort: in the Western US, an agent-based approach will rely more heavily on capturing individual decision making and the interactions between individuals and certain institutions that would be atypical for a European setting. In Spain, the agent model needs to incorporate a more powerful and more interfering federal bureaucracy, and has to take much more care in the design of the institution and its relation to the individual. Nevertheless, the important dimension to be explored here is the tension between individual and institutional action as a dynamic affecting how ground water banking and conflict are interrelated.

In this thesis, then, comparison between the regions is not treated as an opportunity to exhaustively detail and test the institutional differences and somehow correlate them to a systemic conflict response to ground water banking. The level of detail that can be incorporated into and simulated with an agent-based model restrict the extent to which complex and nuanced conclusions can be drawn about institutional influences on conflict specific to setting. In this thesis I am concerned, first and foremost, with generalizable theory on linkages between institutional capacity and conflict, generated through socio-hydrological simulation. However, I am also interested in both the theory and practicality of modeling individuals and institutions in different settings: does the Spanish setting - both in character of individuals and influence of institutions - differ so much from the US setting that the fundamental cognitive models of agents have to change? If so, how? These are some of the questions that will be explored in parallel to the main thrust of the thesis.

2.0 ... Problem statement

With this thesis I hope to contribute to addressing the following problems:

- *The problem of sustainability in water resources management*: whether we can hope to mitigate adverse environmental consequences, or otherwise enhance the sustainability of agriculturally-dominated water systems through the judicious use of institutions rather than infrastructure;
- *The problem of the 'universal socio-hydrologic agent'*: can agent-based modeling across international and cultural boundaries be accomplished with the same fundamental cognitive tools and internal conceptual models?

I am structuring the investigation around one major hypothesis and associated research question, and one sub hypothesis and sub question. These are laid out and discussed below.

2.1 ... Study purpose and general approach

In this thesis, I propose to use agent-based computational simulation to explore the societal and environmental response to different institutional scenarios in Spain and the western US, for the purposes of: generating generalized understanding of the links between institutional capacity and water conflict; contributing meaningfully to the search for solutions that balance social, economic and environmental needs in the two regions while mitigating or avoiding conflict; and contributing to theory associated with the concept of a universal socio-hydrologic agent.

My general approach has as its foundation the construction of two agent-based models, one for each system. Each model represents, with some key and major abstractions and simplifications, a number of individual and institutional actors within each water resources system, including their interrelations and decision-making characteristics. The Idaho model incorporates a water simulation module based on a pre-existing hydrologic tool from the University of Idaho. The Albacete model incorporates a simpler, more illustrative 'bathtub' model of the Eastern Oriental aquifer constructed specially for this application. Both hydrologic simulations are intended to allow a comparative analysis between the social and environmental implications of two broadly defined simulation scenarios: the implementation of a new institution, groundwater banking, as an accounting system to handle deliberate recharge and discharge to and from the aquifer (defined as institutional change in this setting: Contor and Johnson 2005); and a business-as-usual future where no institutional changes are implemented. Both scenarios imply that no new infrastructure is added to the system; in both cases, existing wells are used for the purposes of interacting with the aquifer as a 'water bank'.

An exceptionally important point to note here is that neither simulation tool is intended to be predictive. There are fundamental reasons why this is so: primarily, the quality of data being used to generate the structure and content of each model is significantly below par for the purposes of policy-relevant predictive modeling. While this constrains the utility of each model in a real decision-making environment, it does not constrain some careful and conservative interpretation of the implications of each simulated scenario for their real world counterparts. It is my intention that each model be treated as an exploratory and illustrative exercise, marshaling mixed social and hydrological concepts and data to explore general trends in system behavior. The second point is that I have personal reservations as to the utility of attempting to predict social behavior through the medium of agent-based modeling. I share the view advanced by Tesfatsion (2002) and others that agent-based modeling in a socioeconomic context is best suited to developing theory rather than predicting real world outcomes (although I am not averse to using theory to make carefully bracketed predictions as to the general qualitative nature of those outcomes). In addressing agent-based computational economics, Tesfatsion suggests one of the benefits to the approach of using simulated (see also Epstein and Axtell's work in this regard: Epstein and Axtell, 1997) synthetic societies, is the ability to "demonstrate constructively [i.e. generatively] how global regularities might arise from the bottom up, through the repeated local interactions of autonomous agents" (Tesfatsion, 2002). In the present instance, I advocate the use of agent-based models to enhance existing theories on the linkages between institutional capacity and water conflict, not to predict whether or not a particular institution will lead to a certain degree of a certain kind of conflict if it were ever implemented in a real world system. There still exists a great gulf between our representation of human cognition inside computational simulations, and the real nature of that cognition; this is particularly true of the reasonably simple models I create and run for this thesis. My cognitive models borrow from older work of Artificial Intelligence and Cognitive Neuroscience researchers, but in no way represents the latest or the best way to represent agent cognition as proxy for human cognition. Consequently, given the continuing paucity of data and significant conceptual deficiencies, I am most definitely not applying agent-based modeling to anything but explanatory theory building. However, to reiterate, this will not and I believe should not stop me from drawing some *general, carefully circumscribed implications* for real world systems.

2.2 ... Research Questions

1. **Major Question**: theories exist which suggest that higher institutional capacity correlates with reduced conflict frequency and severity; can agent-based socio-hydrological models of two institutionally rich, conflicted water resources management settings contribute to this theory, and if so, what kind of theoretical relations do they suggest?

2. **Sub Question**: what do the significant institutional differences between the western US and eastern Spain mean for an attempt to build a more generic agent architecture (cognition and action mechanisms) that could be used to simulate socio-hydrologic systems across political, geographic and cultural borders?

2.3 ... Major Hypothesis

"Any change to institutional capacity will have an effect on the dynamics of water conflict in an artificial social-hydrological system"

With this hypothesis I am advancing theories of system change for each of the Spanish and US settings. The hypothesis draws on the concepts of episodic and continuous change (Weick and Quinn 1999). According to these authors, systems prone to episodic change are those that: are focused on efficiency in resource distribution and production, and short-term rather than long-term adaptability; are highly institutionalized with powerful norms. Systems prone to continuous change are those oriented towards continued translation of learning and experience into new practices.

The ESPA area has only a few key water-related institutions, all of which are well-entrenched, is socioeconomically and politically focused on optimal distribution of a scarce and over-allocated resource, and has a social system knitted together by the shared norms of practicing a century of large-scale irrigated agriculture. The introduction of a new institution or the alteration of an existing one is consequently rare and deliberate, accomplished through drastic top-down change. The creation of Water District 120 in 2002, for example, was only accomplished through the intervention of the Director of the Idaho Department of Water Resources (IDWR) under statutory authority (IDWR 2002). I thus characterize the ESPA as a social-hydrological system that is institutionally frozen and consequently prone to episodic change.

Institutions are even more powerful and well-entrenched in Albacete, but the system is far more receptive to major institutional change: the requirements of the WFD are actively creating a new set of institutions that have serious local and regional implications. Prior to the WFD, most WRM institutions regionally and nationally were based on a utilitarian paradigm: hydraulic exploitation for maximal economic benefit to citizens, at minimal personal cost (Sauri and del Moral, 2001). The major inter-basin water transfers were designed, so Sauri and del Moral suggest, to achieve "water for everybody at no cost" (*ibid*, 1). The WFD adjusts WRM priorities to include strong environmental considerations, so this is a time of considerable institutional flux in the region. With or without the WFD, however, government in general retains a strong level of control over the direction of water management and use. Whatever may or may not be happening at higher institutional levels, the agricultural system in the region has long been focused on exploiting the resource for shorter term gain (Maass and Anderson, 1978). This suggests an interesting conflict between a macroscale shift in institutional emphasis, but a strong local interest in economic gain through exploitation of a scarce resource. I thus characterize Albacete as a system embodying dual levels of change: a socio-hydrological system that has a dynamic, continually evolving institutional framework at a macroscale, and an institutionally frozen environment at a more local scale. However, the only very recent emergence of irrigated agriculture (the last half-century) in Albacete compared with nearby regions such as Alicante (*ibid*) may suggest a more flexible institutional framework, or the dominance of individual choice rather than institutional imperatives.

Despite the differences between ESPA and Albacete, both systems are tightly coupled to external or internal perturbation: in ESPA, this is partly because of a severe over-allocation of resources but more likely due to an extremely limited range of legal and political institutions available for handling emerging conflict. There is a significant amount of water above and below ground the ESPA region, in other words, but serious legal and political limitations on the possible solutions to conflict. In Albacete, the tight coupling appears to be due more to the severe over-allocation of water. The aquifer is heavily over-abstracted, and when the aridity of the region is considered along with an infrastructural status quo that delivers most of the region's water to the older irrigation districts on the coast, we see a tight coupling between the system behavior and any change to its hydrologic conditions. The system is therefore indirectly coupled to institutional change, since any institutional modification that somehow changes the availability of water (whether through direct volumetric change or otherwise an access change) is likely to cause a shift in the rest of the system.

In tightly coupled systems, any significant perturbation, whether institutional or environmental will result in an immediate shift in some element of system behavior. I am assuming for both regions that political conflict is the pressure valve that indicates a malfunctioning water resources management framework: a party or parties is being harmed in some way by some wider system process or specific actor behavior, and so responds by complaining or initiating a legal proceeding. Consequently, I hypothesize the link between conflict dynamics and the introduction of a new institution (a major system perturbation) in both regions.

2.4 ... Sub-Hypothesis

"Institutional and environmental differences between modeling settings do not necessarily mean that a fundamentally new socio-hydrologic agent must be built for each"

Achieving a more generic foundation to the simulation of socio-hydrologic systems is not something that has attracted much practical interest in the agent-based modeling community. Yet it is a concept that is frequently called for in the wider field of social simulation (Mentges 1999, Schmid 2000). This disparity is probably not for want of trying, since developing a single generic agent implies settling upon a single structural model for representing human cognition and behavior inside an ABM (Amblard 2001), something which neither cognitive neuroscience nor agent-based modeling have settled upon. Given the conceptual and practical challenges to achieving that level of granularity in a 'generic' agent, I am not hypothesizing that a single, generic structure for a socio-hydrologic agent can be constructed if it advances a single interpretation of human cognition and behavior. However, I do believe the following: that both the broad definition and basic structure of a socio-hydrologic agent can be engineered so as to be portable from one WRM setting to another. This is because the broad intent of modeling a socio-hydrologic agent varies very little between modeling projects and model settings: the agent must interact with society, economy and hydrology/environment in competition for the water resources available to the system. This lack of variation should mean we can improve upon our concept of an agent in the socio-hydrologic simulation setting and advance some propositions for what a socio-hydrologic agent looks like regardless of the real world scenario being modeled. To address this hypothesis, I will attempt a broad definitional and structural comparison between the agents within two models constructed. Note that I am not intending to prove that a generic agent is universally possible, simply that switching real world setting should not necessarily mean the agent structure must also fundamentally change. My core intent is to build theory in socio-hydrologic simulation by offering some 'socio-hydrologic agent constructs' based on real comparisons between two models built for diverse settings.

2.5 ... Construct definition

Conflict as Aubert (1963) observed, "is ambiguous. It is applied to neural processes, to internal psychic states and to individual choice of action" (Aubert 1963: 26). Conflict is a general state of antagonism, a "tension between two actors irrespective of how it has originated and how it is terminated" (*ibid*). In multi-agent systems literature, agents are either cooperating or conflicting (Zlotkin and Rosenschein 1991), but more sophisticated agents that are representative of human actors need to experience and practice degrees of conflict – some conflict is productive, but there is usually a threshold over which conflict becomes damaging (Beratan and Karl 2005). However, for the operationalization of conflict in the context of an agent-based modeling effort that faces real constraints on available time and resources, I define conflict more simply: as one instance of an agent or group of agents taking a 'court action' against another agent or group of agents. Conflict dynamics are essentially a function of both severity and frequency of conflict: a small number of very severe conflicts has the same weight as a larger number of very minor conflicts, for example. The level of conflict is neither significantly constructive or destructive (although it does take agent resources to raise and maintain a 'court action') to individual agents up to a certain threshold at which conflict becomes so frequent and so severe that the model grinds to a halt. In the Idaho model, a court action consists of registering a complaint to the State Management Entity (SME: more on agent typologies below) about depletion of an allocated water right, and is recorded by the SME as a collection of three data points: the plaintiff, the defendant and the amount of water lost claimed as injury. The SME will, depending on the amount and source of such suits, from time to time issue curtailment orders to the defendants. This is not designed to represent any serious attempt to fix the problem, but to simulate the effect of periodic disturbance of the institutions of water management by a higher level institutional entity. In AlbAgent, conflict is represented by three grades of severity: informal complaints, where a Farmer agent registers a minor gripe with the government (CHJ: see more on agent typologies below); formal complaints, where a Farmer agent registers a more serious issue; and a protest, which is roughly the equivalent severity of an Idahoan court action - but termed a 'protest' because the Spanish legal environment regarding water is considerably less litigious than the western United States. For both models, conflict frequency is operationalized as the number of court actions/protests and complaints occurring within each time step, and conflict severity as the number of agents making court actions/protests and complaints within each time step. This is intuitively sensible, since one agent may be particularly enthusiastic in letting the government agent know of its disgruntled state (and may be uniquely able to support the costs of such action), in which case a high frequency may be posted. But since only one agent is registering all this conflict, the severity is not significant. However, where the entire population of irrigator agents is involved posting conflicts in one time step, something is clearly wrong.

Institutional capacity in an agent framework is defined as a composite measure of the presence (is it present in the system), capacity (what is the range of its functions, and what supporting resources does it have) and quality (the longevity, efficiency and effectiveness) of an agent institution. The definition of institution is based on Searle (2005): "an institution is any collectively accepted system of rules (procedures, practices) that enable us to create institutional facts [a fact that does not exist without its associated institution]" (Searle 2005: 21). An institutional enhancement would be a modification to an existing institutional structure, or the creation of a new one with the intention of contributing to less conflictual water resources management. Three forms of social institution are operationalized in this model: a basic system of flexible and inflexible rules governing agent behavior at the macro-level (i.e. a legal and economic framework); an abstract organizational structure with intentionality and an influence on agent behavior and system outcomes (i.e. for the Idaho model we have the SME, a state agency concerned with and mandated to oversee water management in the region; for the Albacete model, we have the CHJ, a regional agency concerned with managing water in the Rio Del Jucar basin); and the ground water banking institution itself, which overlays new rules of operation and interaction for both individual agents, their social institutional rules, and the state/regional water management agency.

The definition of artificial social-hydrological society is drawn from Epstein and Axtell (1996): in an artificial social-hydrological society, “fundamental social structures and group behaviors emerge [but are also specified] from the interaction of individuals operating in artificial environments [in this case, based on hydrological and agricultural data and sub-models] under rules that place only bounded demands on each agent’s information and computational capacity” (Epstein and Axtell 1996: 4).

Ground water banking is variously defined elsewhere as “the storage of excess wet year supplies in subsurface aquifers” (Purkey et al 1998), or “a means of reallocating or transferring the use of water through some kind of centralized management entity” (Cartron et al 2002), but these are not exhaustive – the term takes on meaning specific to the context in which it is being considered. The ground water banking project at the University of Idaho (USBR/IWRRI 2006) and other feasibility studies (e.g. USBR/IWRRI 1999) suggest some potential scenarios for the shape and function of a groundwater banking system, addressing issues of getting the water into the ground and out of it again and then distributed to users, all in a socially and economically efficient and non-conflictive manner. Getting water into the ground might be achieved via the installation of large injection wells for aggressive aquifer recharge of wintertime runoff, the diversion of surplus flows during high flow periods onto ponding sites where water would infiltrate into aquifer storage, or utilizing existing ground water pumping infrastructure (the most likely interim solution). Water would flow out again through existing abstraction wells, and through natural groundwater-to-surface hydrogeologic connections. Note that the concept for Spain would likely differ, since the pumping infrastructure is more limited in sophistication and scale. It is possible that deposits into the bank (or aquifer) would be conducted through the use of virtual water, in the sense that foregoing the right to pump water would be considered a deposit. Leasing water from the bank/aquifer would be accomplished in the same way in Albacete as in Idaho - direct pumping, most likely through pre-existing wells. The management of this new flux would most likely be achieved by an accounting system of groundwater debits and credits, tracking the source and destination of parcels of water in the storage zone and providing for the trading of water credits according to the requirements of the users, managers and the environment. The groundwater banking concept is operationalized as an entire scenario – a specification of a managing institution (coordinating the banking system and adjudicating disputes) and associated institutional arrangements (rules of engagement with the system that agents have to follow to participate in the bank).

The ground water bank concept is operationalized in both models using a set of rules that apply universally to agents participating in the banking system, and provide options as well as limitations for them to inject, withdraw and trade ground water as a commodity.

Socio-hydrologic agent is a concept without common currency in either hydrology or agent-based modeling (or any other water-related fields, to my knowledge). The concept of 'socio-hydrologic systems' is more frequently heard and so forms the foundation of my definition. A socio-hydrologic system, or a socio-hydrologic approach to viewing a system, is used here in a sense defined by Mohorjy (1989): integrating "the hydrologic and socio-economic aspects of water resources planning" (Mohorjy 1989: 1). In other words, a socio-hydrologic system is one where social, economic and hydrologic subsystems are causally linked. In Albacete, economic and sociopolitical choices have had strong effects on the state of the regional aquifer, and the evolving state of the aquifer and other dimensions of the aquatic environment (such as water quality) continue to have strong influence on the regional economy and society. In the western US, the entire agricultural system and associated community fabric have evolved around a complex system for allocating water; the natural and not so natural cycles of the river system are tightly interwoven with the fortunes of the social and economic system. This is not to advance that the social-hydrologic coupling is the only relation of consequence in either setting. Both are complex settings where several dependencies on multiple levels exist.

Given my definition and assumption of coupled systems in both settings, I propose the concept of a socio-hydrologic "agent" as a proxy for some individual residing within and interacting intimately with a socio-hydrologic system. To be a socio-hydrologic agent, the entity must have a dual relationship with both water and society/economy. The irrigation farmer is the pre-eminent example in both settings: in the American West, irrigation farmers still sit at the center of the hydraulic society that a century of Federal subsidy has built (Worster 1992). In Albacete, the irrigation farmer is the principal reason why the aquifer is heavily depleted and the current supply and quality crisis is unfolding (Martin de Santa Olalla Manas et al 1999). The farmer in both settings sits at the nexus of economy and environment: in Spain, the EU subsidy drives overproduction at the same time as the WFD drives conservation and habitat restoration; in the American West, Federal subsidies shift production to water intensive crops in areas that without irrigation would be desert, even while profits sink as wetter farmland production forces prices down. For the purposes of simulation, then, a socio-hydrologic agent is an entity affected both by hydrology in the raw (precipitation, floods, pollution, etc) and hydrology translated into social and economic dynamics (water policies, changing prices, etc). However, this is not the limit of the definition: to be an agent, the entity must have some outward effect on the world. A socio-hydrologic agent in particular must effect change in the social and hydrological systems associated with water for its particular setting. The focus of my thesis simulations is on the farmer as a socio-hydrologic agent, affected by and effecting change in the social, economic and hydrologic systems within which the agent is embedded. Less numerous in the models are agents representing government, power companies, canal companies and fish farms. All of these are still socio-hydrologic agents, since their actions directly affect the hydrologic system and associated institutions (or they may in fact represent one of those institutions), and they are themselves affected by hydrologic and socio-hydrologic change.

2.6 ... Modeling precedent and theoretical base

Considerable effort has been devoted in the agent-based modeling (ABM) research community towards articulating typologies for ABM applications. For this work I take as a theoretical base the work of Boero and Squazzoni (2005), who argued that "empirical knowledge needs to be embedded into modeling practices through specific strategies and methods" (*ibid*: 1.7) and suggested a taxonomy of ABMs in which "case-based models" form one key class: models with an "empirical space-time circumscribed target domain" (*ibid:* 3.4). Case-based models are theoretically thick, have micro-specifications for individuals and interactions, and serve to "investigate empirical macro properties" (*ibid*: 3.5). Finally, they suggest that "the goal of the model maker is to find a micro-macro generative mechanism that can allow explaining the specificity of the case, and sometimes to build upon it realistic scenarios for policy making" (*ibid*). This forms the central theoretical basis of my approach: appreciating the complexity of a particular setting (Ragin 1987) while seeking to generate local theoretical explanations that can be extended to other settings and to a higher body of theory. This project is exploring the emergence of conflict in "highly complex, non-linear, path-dependent and self-organizing" (Macy and Willer 2002: 144) socio-hydrologic systems. The methodological approach is characterized (after David et al 2004) as Socio-Scientific (using a "theoretic framework of social and/or environmental sciences to model social and environmental phenomena"; David et al 2004: 3.11) and as Socio-Concrete (modeling and simulating "concrete social systems based on direct observation and statistical data, in order to understand social and institutional processes and phenomena" (*ibid*: 3.19).

Water or other natural resource focused agent-based models are prolific in the ABM world: Becu et al (2003) modeled small catchment water management in northern Thailand (the CATCHSCAPE model). In this model, the major hydrological features of the catchment were simulated, as were farmers' individual decisions, with exposition of impacts on local water management, economy and landscape evolution. Espinasse and Franchesquin (2005) simulated hydrological management of the Camargue ecosystem in southern France, representing human activities (e.g. fishing, agriculture and nature exploration) as agents and coupling these activities with a hydrological model. Feuillette et al (2003) used a multi-agent model to test hypotheses on the importance of non-economic interactions between farmers over water in Tunisia: they modeled the water table and user interactions to explore the results of different management interventions. Castella et al (2005) explored the use of intensive collaborative work with stakeholders to build an agent-based model of agro-ecological land-use changes in northern Vietnam. These are a small sampling of an emerging and increasingly robust body of research using agent-based simulation to explore social dynamics associated with natural resources. This work falls somewhere between the highly participatory approach of Companion Modeling using the CORMAS platform (e.g. Barreteau et al 2001), and laboratory-based approaches using the RePast or Swarm platforms exploring sociobiological or micro-sociological theory (Minar et al 1996): agents are specified to a higher degree of detail than in Swarm-type models, but stakeholders will not be engaged to the extent that the CORMAS approach suggests. This project emphasizes validation of outcomes using stakeholder surveying (David et al 2004), where this has been possible.

Despite the broad precedent of using agent-based models to explore natural resources management questions, there is little precedent for exploring conflicted water resources systems through agent-based simulation modeling, and conducting loose comparative analyses of the results of simulations for different settings. The research I outline and conduct in this thesis is novel in that respect.

2.7 ... Sources of empirical data

In this discussion and onwards in the rest of the thesis, the two models are referred to by their development names: GWBSIM (Ground Water Banking Simulation - Idaho) and AlbAgent (Albacete Agent Model).

The difference in the provenance of the two models is nowhere clearer than in the sources of empirical data on which model is at least partly based. GWBSIM is partly parameterized through a series of interviews with approximately 25 stakeholders from the region, and partially validated with a workshop during August 2007. AlbAgent is based entirely on secondary data sources: statistical information from the Spanish national statistics agency, and geospatial information from local and regional contacts. Informal validation opportunities were had in October and December 2007, but otherwise there has been no serious stakeholder-oriented validation for AlbAgent. This exposes a more fundamental difference in the two models, which can be measured in complexity. GWBSIM was a year in the making, whereas AlbAgent was less than half a year in production, and the result is differences in the functional complexity of each model. However, despite being less complex, AlbAgent replicates the basic and essential structures of GWBSIM; the agent cognitive models are very similar, the algorithmic set up of the ground water bank is nearly identical in concept, and the mechanisms for representing and tracking conflict in the system are the same. The implications of model differences for analytical comparison are discussed in later sections, and for the moment I will restrict myself to discussing what empirical data was gathered, as well as where and how it was used in each model.

2.8 ... GWBSIM empirical data

Primary data for structuring the cognition of the agents comes a series of interviews I conducted in January 2007 with around 25 key stakeholders up and down the Eastern Snake Plain. I structured these interviews to elicit responses from stakeholders that could be used to flesh out the BDI (Belief-Desire-Intention) cognitive framework used to develop the agents. Data for parameterizing the hydrology and economy came from the IDWR (time series hydrologic data), the University of Idaho Agricultural Economics Research Service (AERS; for crop pricing and production costs over the period 1980-

2000) and the National Oceanic and Atmospheric Administration (NOAA; for historical precipitation and temperature data). I conducted additional validation work in August 2007 with a group of stakeholders derived mostly from the USBR's Snake Plain Groundwater Banking Project advisory committee. A basic interviewing guide was used to help structure questioning, and this is included in the Appendix. However, discussion tended to vary significantly from the script. A brief discussion follows below of how the data gathered in these interviews was used to help develop the cognitive structures of the model. 23 interviews were conducted with a range of stakeholders from around the region: while specific individuals cannot be named, 'types' of stakeholder we spoke with included:

- Surface water irrigators
- Ground water irrigators
- Canal company staff
- Federal, state and local water management staff
- Aquaculture representatives (spring users)
- Regional academics

The interviewing questions were designed to seek as much information as possible within the following categories:

1. *Beliefs* – knowledge about the natural and social worlds; a belief would be "groundwater and surface water are poorly connected in this location due to an intervening clay layer" or "John is a member of the committee and is on good terms with all the members".
2. *Needs* – fundamental, immediate and survival-oriented drivers of desire and intention; a need would be "I need to pay off a loan before the end of the term in order to stay solvent".
3. *Interests* – secondary, longer-term drivers of desire and intention, arising from combinations of fundamental *needs*, and other non-survival-oriented drivers; an interest would be "improve financial security to enable the purchase of new farming equipment and reduce dependency on loans".
4. *Positions* – socioeconomic and sociopolitical position of an actor relative to other actors within a context; positions would be "I am the head of this irrigation district" or "I have participated in this committee for several years and consider myself a committee member".
5. *Desires* – explicit assignments of goodness to different states of the world based on implicit complementary combinations of *needs*, *interests* and *positions*; a desire would be "[Implicit]: given my *position* within the community, my immediate *need* to ensure the survival of my farm and my long term *interest* in building my ownership of water rights, [Explicit]: I think changing the status quo in local water resources management is an excellent idea".
6. *Intentions* – explicit committed plans arising from implicit reasoning about desires in the contexts of beliefs; an intention would be "[Explicit]: I intend to buy this water right, [implicit]: since it meets my needs and interests, and I know that

a poor groundwater-surface water connection exists in this area so I am not losing water to the aquifer".

7. *Moral sentiments* – significant personal emotions towards another individual, group of individuals or formal organization, which affect *intentions*, *interests* and *desires*; an emotion would be "I don't get on with X because he did not support me in the last committee meeting".
8. *Social norms* – the actor's own perception of tangible or intangible social pressures acting on his own decision-making, influencing the selection of *intentions*; social norms would be "transparent handling of water transfers is important to the community" or "we usually work together to resolve our differences – it's characteristic of how we do things here".

The semi-structured nature of the interviewing meant that is was not possible to explore all these themes systematically or code them accordingly, but the results of the conversations were parsed into the model as much as possible along these lines. The following is a set of excerpts from one transcript, with comments detailing the use of the information in the model's structure. Note that due to a confidentiality agreement, the identity of the interviewee cannot be disclosed. 'SH' denotes 'stakeholder', and 'I' denotes 'interviewer'.

General overview:

I: What do you all see as the critical issues in the ES at the present time?

SH: The biggest problems… To me it's the conjunctive management issues. Also, the interface between our legal mandate and where we'd like to go.

The interpretation in the model is in the general assumption of institutional and legal inflexibility. The larger organizations with a role to play in the Snake (such as the CCs and the SME) are restricted in their ability to interpret the law. They perform their functions and do not attempt to improve based on past experience on to adapt to changing conditions. Thus one of the core 'interests' of this agent's mission is interpreted as being to maintain the status quo and the agent's mission, while imparting that agent with a certain amount of stress related to its inability to respond to change given the restrictive legal framework. This could represent a 'social norm' widely prevalent in the regional society and influencing how stakeholders will handle risk.

Knowledge of other agents:

I: What's your understanding of the average user's understanding of the complexities in the system?

SH: There's a general lack of understanding. Within the water user community, there are probably folks that know there's an issue out there, but not much details of what the issue is. There's perhaps a minority of less than 10% who are up on all aspects and facets of the issue. Most people have a very surface understanding of the aquifer, a very elementary understanding of the issues. I don't think things run very deep, they don't have the knowledge or the detail of the complexity there.

The interpretation in the model is in the level of trust agents have in the ground water model. The model makes the assumption, based on this interview result and others, that most agents have a very poor understanding of how the aquifer works and how the Eastern Snake Plain Aquifer Model simulates the behavior of the aquifer. With a poor understanding is likely to come a lack of trust and increased suspicion, and these variables are modified accordingly.

Selection of agent typologies:

I: You mentioned urban growth. Is that a pretty steady trend? Are you thinking strategically in terms of long term urban growth or do you see that as an uncertainty?

SH: All of southern Idaho is growing at a pretty aggressive rate, and I would foresee that continuing. Around Twin Falls, Idaho Falls, Pocatello. It's not something that plays a big role at this point, but particularly in relation to any banking concept there may be some future issues.

…

I: From this stakeholder list, please pick out the stakeholders who you work most closely with, or find your decisions influenced by the most.

SH: … You don't have on here the recreation public. The eastern Snake's reservoir system has flat water recreation boaters, fishermen; in some of the lower reservoirs there are kayakers, fishermen. That's a big public with an important role, especially in the Palisades, Jackson area.

The first excerpt has been interpreted several ways in the model: other accounts also supported the impression that M&I users were increasingly important in electoral and economic terms, but were not significant influences at the present time on water use and management. Both in interviewing and in the validation workshop in August, the presence of M&I users as agents in the model appeared to be a possible future option, but not a make-or-break necessity. Consequently, M&I users are left out of the final model at this time.

The second excerpt is an example of interviewing data not used in the final model structure, but also pending future implementation: recreational users are growing in numbers and political significant in the eastern Snake, and along with environmental needs may represent a major consideration in future and a possible driver of participation in the ground water bank. However, time and memory limitations meant that a recreational user agent was not implemented in the final model structure.

Perception of powerful agents within the system:

I: Form the perspective of other stakeholders, who is the most influential or powerful?

SH: First, the surface water users. Second, it's the ground water users. Then the aquaculture folks are right in there. They're the big drivers, the ones who have hired the expensive lawyers, the ones who have taken issues to the courts. The dairy industry next. After that it probably comes down to those with the biggest space-holding in the reservoirs to the least. But then there's also the Committee of Nine, which was created 85 years ago to be an advisor to the Water Master in the upper Snake.

This short answer holds a wealth of information relevant to the social hierarchies in the system: while surface water users and ground water users were repeatedly among the top few stakeholders considered the most significant and influential, the aquaculture industry (Spring Users in the model) were frequently seen as the most combative and the most able to bring their issue to the attention of the region and state based on their greater level of wealth. This general sentiment was used as a justification to set up the SU agents to be more predisposed to launch a court action and/or complain – not that this was guaranteed, just more likely – than other agents.

Level of conflict in the system:

I: As far as other stakeholders are concerned, have there been any decisions made by stakeholders that you've observed to be particularly contentious?

SH: The calls, principally.

I: From the list, which stakeholders tend to interact with the most conflict?

SH: The IWUA represents the surface water users and is pretty conflictive. The newer organizations, the ground water users, they're getting front and centre these days. Idaho Power certainly causes problems from time to time. In general, there's always friction between water uses - large and small, upstream to downstream. The aquaculture folks have got quite a bit more involved in the last decade, I would say.

I: Conversely, are there any stakeholders particularly open to collaboration?

SH: The Nez Perce forced folks to collaborate for quite a few years. There were many attempts to collaborate between the surface water and ground water folks.

For whatever reasons, they failed. The mood right now is people are resolved in themselves that the next steps will be taken in the court system.

The reference to 'calls' is to the court actions made by downstream surface water users against upstream ground and surface water users for allegedly depriving those downstream users of their legal water rights. This kind of information is enormously useful for setting up the outward-looking belief systems of individual agents – which agents are seen by other agents as being particularly conflictive or hostile – as well as setting up different agent typologies with different inherent predispositions to conflict. In general, the agents do not differ significantly in their 'genetic' tendency to conflict, but certain key facilitating variables – wealth, starting income and water stress – do differ and so agents do naturally vary in their predisposition to launch court actions and complain.

'Nez Perce' refers to an agreement over water use and management in the Snake between the Native American tribes and other water users. The comment on the lack of collaboration and the tendency to rely on the court system to resolve problems was corroborated by several other stakeholders. It is the principal reason why a negotiation option was not included in each agent's conflict resolution options. The default is to complain or go to court, and this was an assumption drawn directly from these kinds of comments. The reality is that there are multiple steps between complaints and full-blown court actions, including mediated settlements and negotiated mitigation plans, but to reflect the apparent mood in the system towards conflict, the agents were set up without the general ability to negotiate or collaborate in any significant way. Considerations of time limitations were also a factor in this decision.

Model trust:

I: Does the lack of trust in the model in certain key areas represent an obstacle?

SH: When you talk about shutting off certain wells that's where issues will come up. People will question specific curtailments based on the model. The trout industry has put advertisements in the paper to convince the public that the perfect model is achievable.

I: Is that in a drive to get a better model made?

SH: They put an ad in the Sunday newspaper a few weeks ago saying that if we would just find fund a few hundred thousand dollars, and only a few months time would take us to generate a much better model. I don't that view is credible. They're suggesting they can get a level of improvement that's only really likely with a massive investment and the drilling of so many wells that the aquifer would no longer be what it is now.

This last excerpt is to support the implementation of the 'model trust' variable. It was clear from this interview and others that the ground water model (which is what is being referred to in this excerpt) was a political instrument as well as a technical one: some stakeholders were committed to getting the perfect model, and in so doing perhaps delay the process to their advantage. Others appeared more committed to making do with the existing technology and confronting the reality that the ultimate decision will not be a technical but a political one. So some sort of specific 'belief' variable relevant to the ground water model with which the ground water bank would be run seemed appropriate: all agents with the option of participating have a certain degree of trust in the model (which can vary over time, as discussed earlier), and other emotions that contribute to the agent's willingness to participate in the model.

2.9 ... AlbAgent empirical data sources

The form and quantity of empirical data used in AlbAgent differs greatly from GWBSIM. Whereas GWBSIM incorporated detailed interviewing data into the socio-cognitive structures and parameterizations, AlbAgent takes a different, leaner approach, building on the experience gained in constructing GWBSIM. This could be accomplished by making some key assumptions that reduced the requirement for gathering detailed cognitive information from stakeholders represented in the model. These assumptions are listed and justified below.

- *General cognitive variables were very similar to those used in GWBSIM*: for example, AlbAgent's representation of agents expressing frustration with the system was similar to GWBSIM: complaints with varying degrees of formality, and formal protests to the government. The slight difference from GWBSIM is that legal action is not explicitly represented. This was viewed necessary to reflect the less litigious nature of water resources management in Spain versus the U.S. Additionally, the GWBSIM structure for representing agent stress was also used in AlbAgent.
- *The general cognitive structures for weeding out actionable plans from a stock of options were assumed to be broadly similar in Spain as the US*: for example, GWBSIM agents only take a particular action after it has been evaluated on a number of counts, such as time relevance, cognitive benefits (does the proposed action change a cognitive variable in some beneficial way), resource benefits (does the proposed action change a personal resource in some beneficial way) and role conformism (does the proposed action conform to the typical action in that situation for the particular agent typology). AlbAgent agents follow the same process, although the exact nature of the implementation is different. The similarity was justified on the grounds that farmers in that environment of Spain may differ culturally from the western U.S., but probably have very similar patterns of practical reasoning since they grow some of the same crops in similar environments.

By assuming broadly similar cognitive variables and cognitive structures, a great deal of empirical data requirement could be dispensed with (and, in any case, was not physically possible). The remaining parameterization requirements for AlbAgent can be broken down into:

- **Hydrologic**: aquifer budget; ground water levels
- **Economic**: costs of production; produce prices
- **Agricultural**: crop mix and distribution among farmers; locations of farm wells
- **Demographic**: farmer population

Hydrologic data was assembled from direct and indirect consultation with regional experts, and from historical datasets stored on the Confederacion Hidrologica del Jucar's website ([Confederacion Hidrologica del Jucar (CHJ), 2006, #18794]). Economic data was derived from the website of the Instituto Nacional de Estadistica for Spain ([Institutio Nacional de Estadistica (INE), 2007, #16788]), and from a diverse range of other sources describing the Spanish agricultural economy. Agricultural data was drawn from the CORINE CLM 2000 dataset as part of a regional geodatabase put together by an MIT team in the fall of 2007. This same geodatabase was also used to generate the base map grid. Finally, demographic data was gathered from INE.

3.0 ... Characterizing Artificial Socio-Hydrologic Systems

In constructing the models, I broke down the real world systems for Idaho and Albacete into environment and actors. The environment is the hydrologic and climatic system. The actors are the stakeholders in the system. Beyond this crude distinction, a complete characterization of either region would have resulted in a large number of actors and some very complex hydrology and climatology. For modeling purposes, both systems were reduced to a smaller number of biophysical, social and economic dimensions. I was more constrained with data for AlbAgent, and so was committed to further reductions in complexity in that model. In the following section I describe, for each model, the essential social and hydrologic components in its socio-hydrologic system.

3.1.0 ... GWBSIM specification

The main actors of interest are agricultural irrigators of various descriptions, non-agricultural irrigators, and a principal state-level management entity. The main environmental processes of interest are surface and ground water flows in response to climatic and anthropogenic forcers. In the model, both biophysical and social components are simulated by agents, but non-social and non-individual agents are purely reactive and non-cognitive (i.e. the Aquifer agent is purely reactive because it is non-social, and the System Management Entity (SME) is purely reactive because it is non-individual and representative of an institution).

Clearly, this is a considerable abstraction of the real system, but for the most part these abstractions and concomitant assumptions are based on the analysis of empirical data derived from recent interviewing conducted with a variety of stakeholders up and down the Snake, and from extensive and ongoing discussions with hydrologists, economists and policy experts at the Idaho Water Resources Research Institute (IWRRI).

3.1.1 ... Environment

The model's environmental simulation encapsulates two main resource components: surface river flow and ground water flow. Ground water is simulated based on the ESPAM 1.1 model, developed by IWRRI hydrologists to capture subsurface flow dynamics across the entire eastern Snake plain. ESPAM 1.1 is a single-layer aquifer model, with sufficient representation of surface geography (the river reaches are represented clearly as separate river cells) that a single layer in GWBSIM was also seen as sufficiently representative. Each cell is implemented as an instance of the Aquifer agent typology. An Aquifer agent is purely reactive and has no cognitive capacity. The principal functional responsibilities of an Aquifer agent are processing time series of reach effects for the ground water banking scenario, providing the spatial representation for the user interface/model output display, and yielding other general environmental information (such as local soil moisture levels) when queried by local agents. The instantiation of the Aquifer class as agents allows the creation of a grid cell graphic that can be more easily queried and manipulated at runtime. To obtain the benefit of coupling with ESPAM without actually doing any coupling, aquifer response functions were used. IWRRI has run 100-year simulations using 1000 acre-foot stresses (i.e. withdrawals of 1000 acre-feet over an initial trimester stress period, and then simulating the response of surface water reaches) to develop tables of response functions for each cell. A response function describes the likely drawdown volume on any one of the 11 surface river reaches in the model, given a certain pumping quantity over a certain period of time. In practice, this allows the agent model to simulate river response to pumping from the aquifer without implementing a coupling between ESPAM and the agent model. Each Aquifer agent has an associated table of response functions for each reach and each of three annual periods for the simulation runtime of 20 years.

Implementation of the river simulation within the agent model was more problematic. Initial planning suggested that coupling with MODSIM (a network flow approach to simulating river flow and allocation of water to irrigation entities, developed by Colorado State University and the US Bureau of Reclamation) was the most credible and realistic option. Time constraints and initial technical problems that slowed development mean that for the present analysis, the coupling was not possible. In its place, an interim solution was developed using a cellular automata approach loosely based on the work of Nicholas and Thomas (2002). The basin is divided up into 11 river reaches, each one defined by a Reach cell. Each Reach cell is treated as a discrete entity that receives ‘parcels’ of water from its eastern/northern neighbor and passes on modified parcels to its western/southern neighbor. A parcel is defined as a discrete quantity of water, in acre-feet, with an acre-feet per second flow rate defined for each cell according to a time series of data for the period 1980-2000. The parcel contributes to the absolute quantity of water in each cell, which is used for irrigation allocations and other functions within the simulation. At specified intervals, a parcel with a volume corresponding to the cell’s flow rate is transferred to the neighboring and downstream cell; at the same time, the cell receives another parcel from upstream. The River cell agent (also described later), is a non-reactive, non-active agent that is instantiated as an agent in the model purely for the purposes of animating the river.

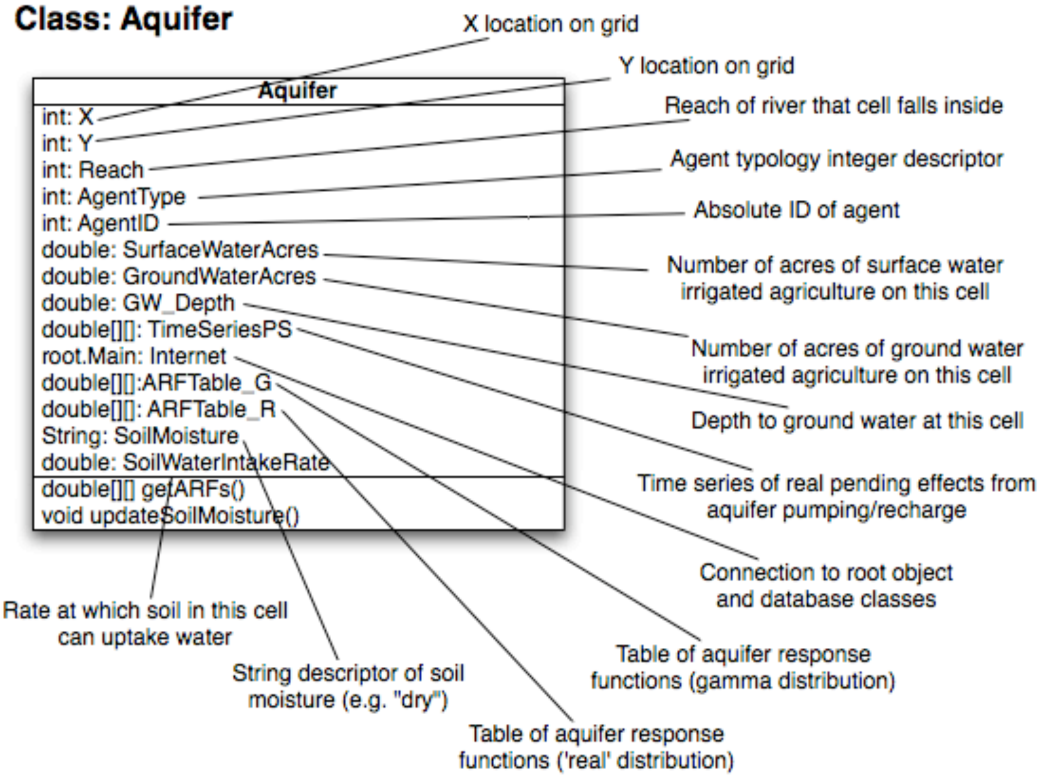


Figure 1: class diagram for the Aquifer agent

Climate is not simulated directly, but implicitly assumed given that the time series data for storage and flow are based on a combination of real climatic and other environmental processes. A 'drought', therefore, is indirectly simulated by a reduction in flow and storage that year, and vice versa for periods of normal or above-average rainfall.

For simplicity, a static GIS provides the backdrop for the agents. By 'static', unchanging is implied, not a lack of communication between the GIS and the agents. The location of the agents on the GIS grid provides for many environmental variables necessary for agent decision making, although the results of agents decisions are not reflected in any change in the map except for their color (bankrupt agents and agents trading ground water credits change color according to their state). The GIS is based on the same model grid used in the official ESPAM 1.1 model. The grid cells are grouped into eleven contiguous reaches. Details for the spatial grid are provided in Figure 2 (after Cosgrove et al 2006).

Grid origin: outside corner of model cell (1,1), Idaho Transverse Mercator (IDTM) coordinates x = 378,416.2 , y = 233,007.2 m / lat = 43.118806, long = -115.49619
Grid cells: 11,451 active model cells, 1 mile x 1 mile square (5,280 ft x 5,280 ft).

Figure 2: georeferencing and spatial details of ESPAM grid

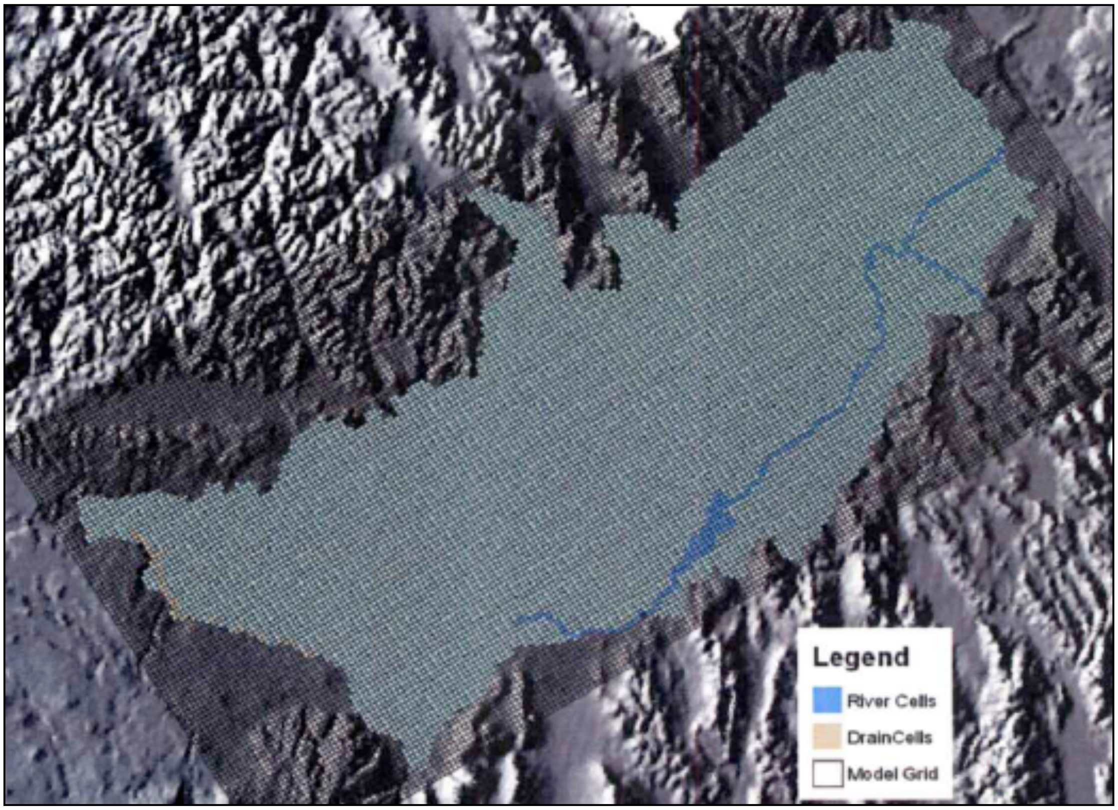


Figure 3: the Eastern Snake Plain Aquifer model grid. Each square grid cell is of 5 km edge length. The smaller blue squares are river squares. The missing section of river in the lower portion of the model corresponds to a reach not hydrologically connected to the aquifer in the main ESPA model.

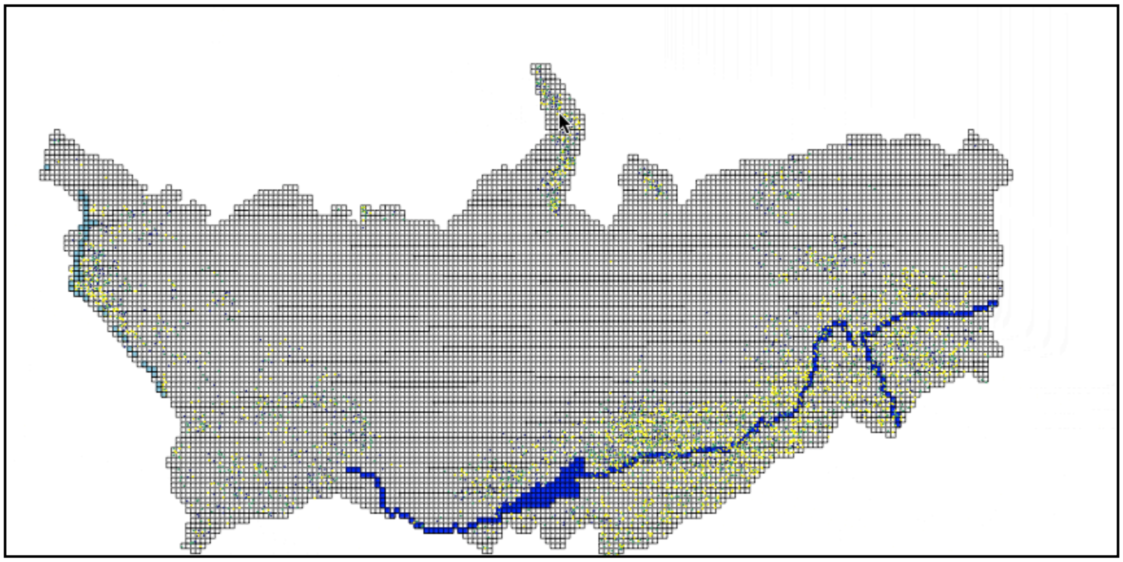


Figure 4: the ESPAM grid translated into the model. Note that GWI agents are distributed all over the grid, SWI agents mostly in the eastern half of the grid close to the river, and spring users in the western most portion of the grid. Dark blue cells are river or lake cells, light blue cells are springs (in the western portion of the grid).

3.1.2 ... Agents

This section discusses the model's agents on two levels: first, at the conceptual level, each agent typology is described in terms of general characteristics - desires, actions, spatial location and so on. Second, at the technical level, I describe how the actual cognitive structure of the agent is realized.

Conceptual design of agents

3.1.2.1 Surface Water Irrigator agent (SWI):

The SWI is interested in planting, irrigating, harvesting and selling its crops in order to maintain an income and pay off debts incurred in conducting an agricultural business. The SWI can choose from between five crops (potatoes, wheat, barley, sugarbeets and alfalfa hay). The SWI obtains its water from the natural and storage flow of the river via the Canal Company agent - note that all SWIs belong to one of 46 canal company agents, which distribute water among the SWIs according to the inflow at the canal’s headgate and the shares that each SWI holds in the canal. Depending on the weighting and combination of a number of factors (including the agent's perception of water availability in the past, its own predisposition to generating conflict, and its current state of income and debt) the agent may seek to file a conflict ‘suit’ (termed a court action in the model) to the System Management Entity (SME) agent. This is the model proxy for a single conflict. Issuing a court action incurs a cost for the agent, and so the agents are more likely to cooperate to issue 'class' court actions rather than issue one on an individual basis. The SWIs have a maximum population of 1518 in any one simulation run, with an average of 700 acres owned by any one SWI (minimum and maximum acreages set at 300 and 30000, with the distribution of owned acres accomplished using a Weibull distribution). In the +GWB scenario, the SWI agent is permitted to deposit water in the ground water bank via managed recharge (ponding of water in areas of land with high infiltration rates). The SWI is initialized with a range of emotional states, including ‘happiness’, ‘initiative’ and ‘risk aversion’. These states are modified by fuzzy logic algorithms known in the model as ‘emotional engines’, as well as by simple feedback loops in response to positive or negative internal or external conditions.

3.1.2.2 ... Ground Water Irrigator agent (GWI):

The GWI is also interested in choosing, planting, harvesting and selling crops each year in order to maintain an income, pay off debts incurred in conducting an agricultural business, and minimize the electricity cost of pumping. The GWI obtains its water exclusively from ground water wells. The GWI agent is not subject to the same reductions in flow as the SWI, but can experience partial or full curtailment of an individual allocation by order of the System Management Entity (under a mitigation plan). The number of GWIs is set at a maximum of 2863 in any one simulation run, with land ownership allocated using the same distribution as SWIs. In the +GWB scenario, the agent can both deposit and withdraw water from the ground water bank using its pumping infrastructure. GWIs have the same emotional engines as SWIs, although with different fuzzy logic rules, and different feedback loops.

3.1.2.3 ... Spring User agent (SU):

In the real system, spring users are non-agricultural users (e.g. trout farms) who rely on a water supply with a very strong direct connection to ground water flow – springs in the downstream (south-western and western) portion of the aquifer. To simplify their representation, these users are designed as industrial plants with a certain production rate and various water quality, quantity and economic conditions affecting production. The agent's principal interest is in maintaining and/or increasing production. Consequently, SUs adopt behaviors to access sufficient water to meet their pre-specified needs (derived from a normal distribution around the average non-agricultural user's water consumption in the ESPA for the past 20 years). SUs are distributed mainly in the lower reach of the river/aquifer system, up to a maximum population of 80.

3.1.2.4 ... Power Company agent (PC):

The Power Company owns several run-of-the-river dams where river levels and flow rates are correlated with electricity generation and the agent's income. The equation used to calculate power generation is shown in Figure 5 below (after NRAES 1978). The PC is thus interested mainly in maintaining flow in the river. The agent is relatively simple from a cognitive perspective, and does not have the same emotional engines and cognitive sophistication of the irrigator agents. The PC is significantly wealthier than all other agents, but cannot participate in the ground water bank. The PC does have the ability to complain and to launch court actions. A distinguishing characteristic of the PC is its ability to launch court actions at a much lower cooperation threshold than other agents, due to its greater capital reserves and more substantial political capital.

$$KW = 0.0846 \times E \times Q \times H$$

where:
KW = power output in kilowatts
E = efficiency of hydroelectric plant (derived from publicly available data on Snake River dams)
Q = water flow, cubic feet per second
H = head, feet (derived from Snake River dam data, Idaho Power)

Figure 5: equation used to calculate power generation from each PC dam.

3.1.2.5 ... System Management Entity agent (SME):

The SME is an amalgamation of the real world functions of state and federal water resources management agencies. The responsibilities of this agent include the allocation of water among the SWIs and GWIs according to water right priority date and quantity, the recording of disputes arising between water users, and the management of the ground water banking system under the GWB scenario. The SME is also able to issue mitigation plans that require GWI agents to mitigate the effects of their pumping on river levels. There is only one SME, and the agent is non-spatially explicit.

3.1.3 ... Technical discussion of agent typologies

The core of the GWBSIM generic agent cognitive architecture (applied to all cognitively-active agents) is as follows: two parallel and constantly running cycles of *reasoning* and *action* (see Figure 6) process agent beliefs, desires and intentions. The coupled work of these two cycles allows the agent to reason and take action multiple times per model step.

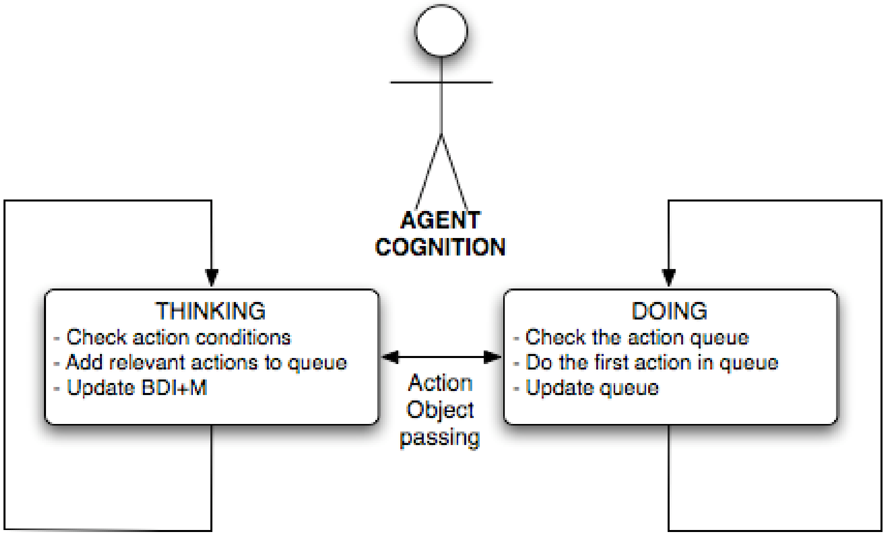


Figure 6: Cognitive architecture of GWBSIM agents. BDI+M = Belief-Desire-Intention+Memory

The left-hand loop in Figure 6 shows how, in each time step, each agent checks the state of its internal, local and regional environments. This stage is referred to as 'condition checking'. A large number of condition checking methods run in each time step, since this stage must encompass all the possibilities for action open to the agent. If the conditions are right for taking a certain action (e.g. for planting: soil moisture is high enough, there is enough water forecasted for delivery to the agent's fields, and the time of year is right for the chosen crop), the agent moves the proposed action to an action queue, part of the right-hand loop shown in Figure 6. In this loop, the action queue is checked at least once per time step, and more if necessary. As each proposed action comes to the head of the queue, more complex conditions are checked. In the case of planting, this would now include checking the state of the agent's capital reserve or credit (for seed purchase), the state of the agent's machinery, cost and availability of pesticide/herbicide/fungicide/fertilizer. Figure 7 displays conceptually how simple condition-action rules lead to plan selection and action implementation.

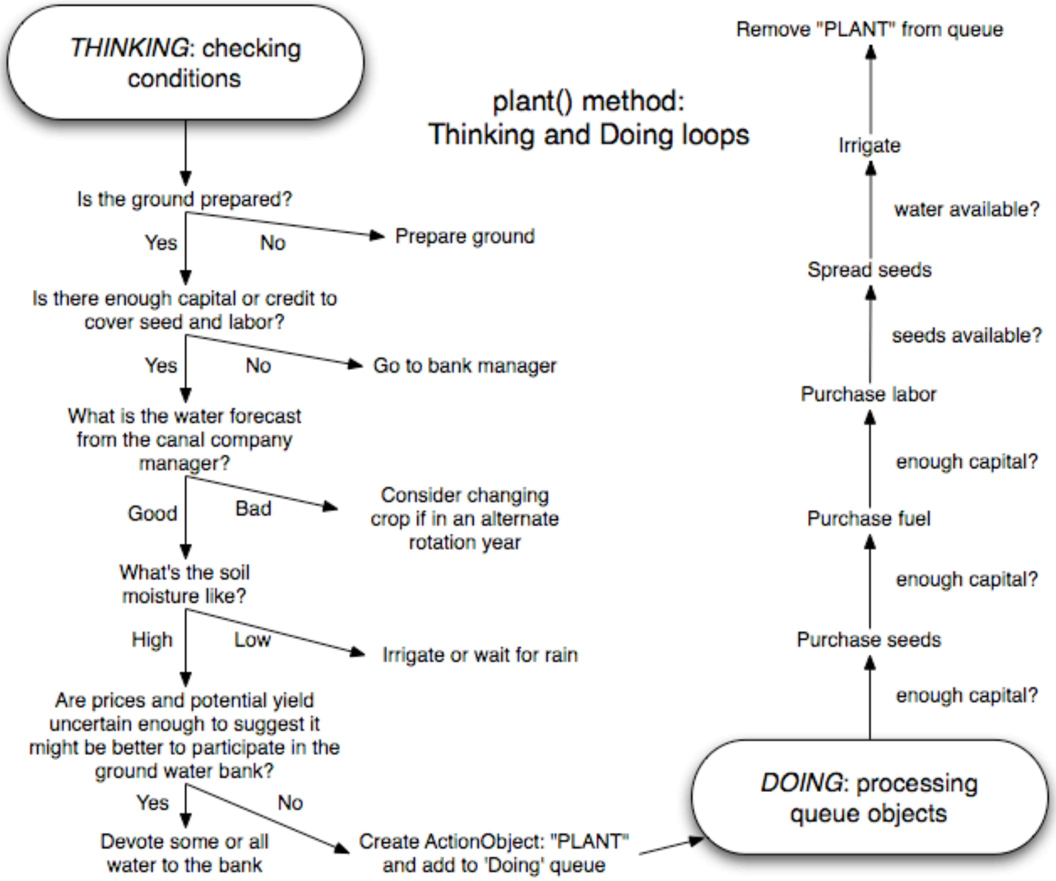


Figure 7: Conceptual representation of cognitive architecture, for plant() method

These reasoning and acting loops require cognitive raw materials, the data inputs which the agent uses to come to a decision on choosing an action and then taking that action. These 'raw materials' are implemented using the Belief-Desire-Intention, or BDI, model (Rao and Georgeff 1999). The BDI model attempts to resolve complex human cognition into a more computationally tractable structure without losing the essence of the human cognitive process. Georgeff et al (1998) suggest that this architectural model has a sound philosophical model of human reasoning; has seen a variety of implementations and practical applications providing for an accumulation of research experience; and provides for an "elegant abstract logical semantics" (Georgeff et al 1999, 1). On these grounds, they advance the BDI model as an efficient and effective way to implement human-like reasoning capabilities.

Within the BDI model, *Beliefs* describe the agent's existing internal set of knowledge about the current state of the world. *Desires* describe the agent's desired state of the world, i.e. how the agent would like the various dimensions of its external and internal environment to become in the short, medium and long term. *Intentions* describe the plans for action with which the agent will carry out the range of actions open to it.

Simplistically, an agent's intentions are designed to alter its external and internal environment so that its beliefs conform more closely with its desires. In practice, the relationship is more complicated, since desires are relevant on different timescales and priorities, and are not always intended as a realizable goal. Sometimes they function more as a motivation to act in a certain direction.

3.1.4 ... Agent Emotions

In addition to beliefs and desires, all cognitively-active agents possess an array of emotions (class: *EmotionObject*). Each *EmotionObject* is a primitive variable with a range 0.0 to 10.0, and corresponds to a particular emotional concept. Some of the major emotions represented in the model include Happiness, Calm, Apathy, Curiosity, Conservatism and Suspicion. Note that the definition of 'emotion' in this context is relatively broad: one could classify 'Conservatism' as a political position rather than emotion, so 'emotion' in its use here refers to any broad cognitive variable that is not well described by the moniker 'belief'. The variables are all identical in nature, but differ in the role they play within agent cognition. Note that the use of emotions within the model is deliberately underweighted, since parameterizing their initial state is highly subjective and difficult to validate at this stage. Two mechanisms within the code govern the modification and impact of emotions: fuzzy logic engines and stimulus-response pairs. Each emotion has a number of fuzzy patterns associated with it: both in modifying the state of that emotion in response to some combination of external environmental or internal agent variables (which may include other emotions), and in forcing change in some other internal agent variable or particular behavioral choice in response to change in that emotion. Figure 8 below shows the overall concept of this dual process.

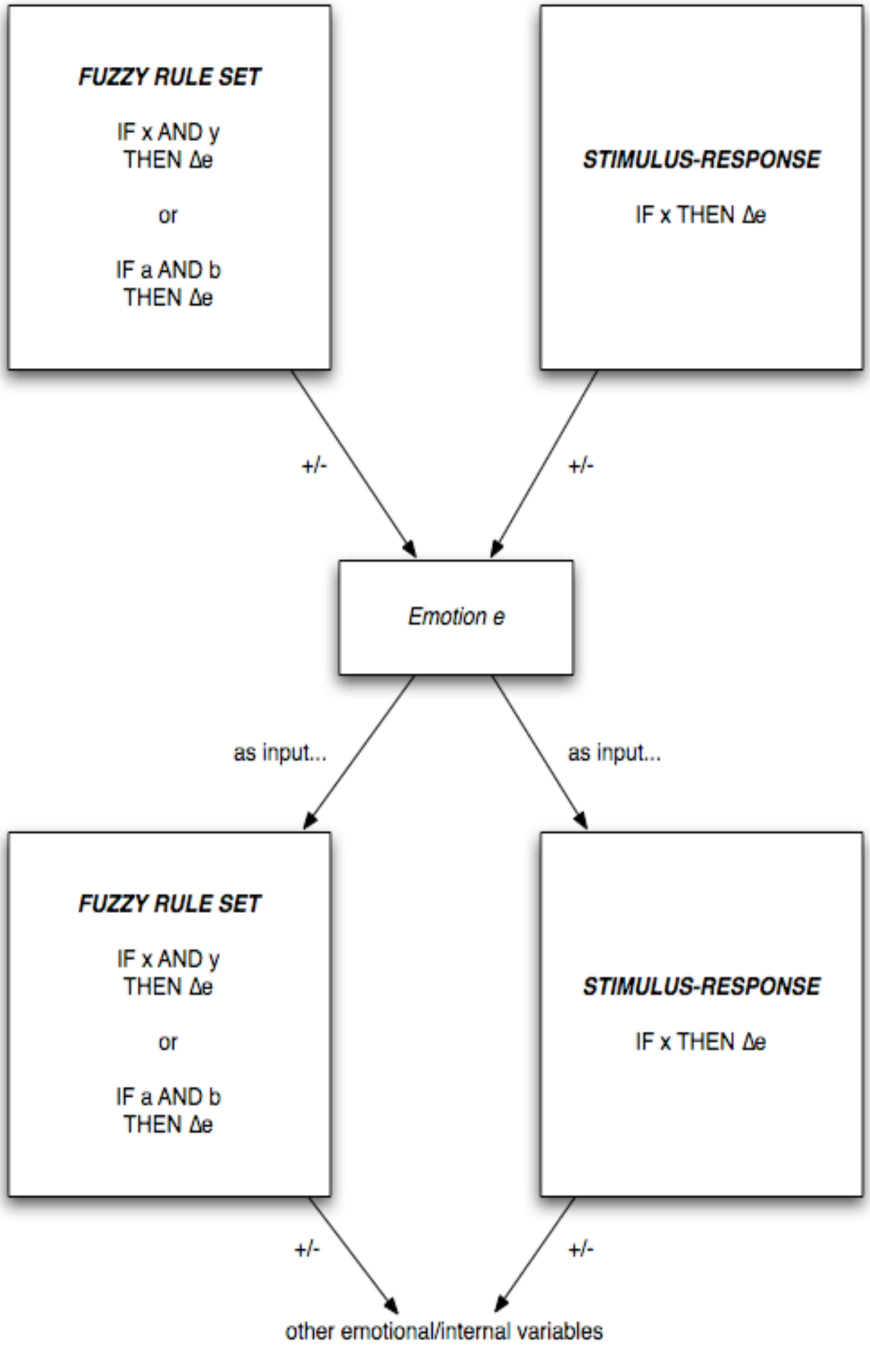


Figure 8: mechanisms by which emotional variables are modified and modify other emotional or internal (BDI) variables and agent behaviors.

An example of some of the rules coded into the fuzzy logic patterns is shown below (for the SWI agent and the 'income stress' variable, Figure 9). Each rule consists of two antecedents and one output. Linguistic variables for the antecedents are defined as:

VERY LOW, MID-LOW, MEDIUM, MID-HIGH, HIGH

Linguistic variables for the outputs are defined as:

INCREASE/DECREASE: MINOR, MODERATE, SIGNIFICANT

e.g.

IF *debt* is MEDIUM
AND *capital* is MID-LOW
THEN MODERATE INCREASE in *income stress*

IF *debt* is HIGH
AND *capital* is VERY LOW
THEN SIGNIFICANT INCREASE in *income stress*

IF *debt* is VERY LOW
AND *capital* is VERY LOW
THEN SIGNIFICANT DECREASE in *income stress*

Figure 9: fuzzy logic input patterns for income stress

Income stress, and its hydrologic equivalent, 'water stress', are catch-all variables that have a larger number of fuzzy logic patterns than most other EmotionObject variables. The higher connectivity between these variables and the agent's internal and external environment mean that both income stress and water stress are agent variables that are strong indicators of the agent's overall state of mind. Generally speaking, the less income and capital the agent has, the higher the agent's income stress will be. Likewise, the less water the agent has, the higher the agent's water stress will be. But the complex interaction of a large number of variables in these fuzzy logic patterns means that change in the stress variables is not always clear or predictable. Figure 10 below lays out, in a simple dependency diagram, an example of emotional variables hard coded to have effects on agent behavior, namely the probability of the agent choosing to participate in the ground water bank. The relationships described in this diagram are for simple stimulus-response effects, but also represent the general effect in fuzzy logic patterns of each input variable on the output variable. The decision to choose certain emotional 'concepts' over others is laid out in the section following Figure 10.

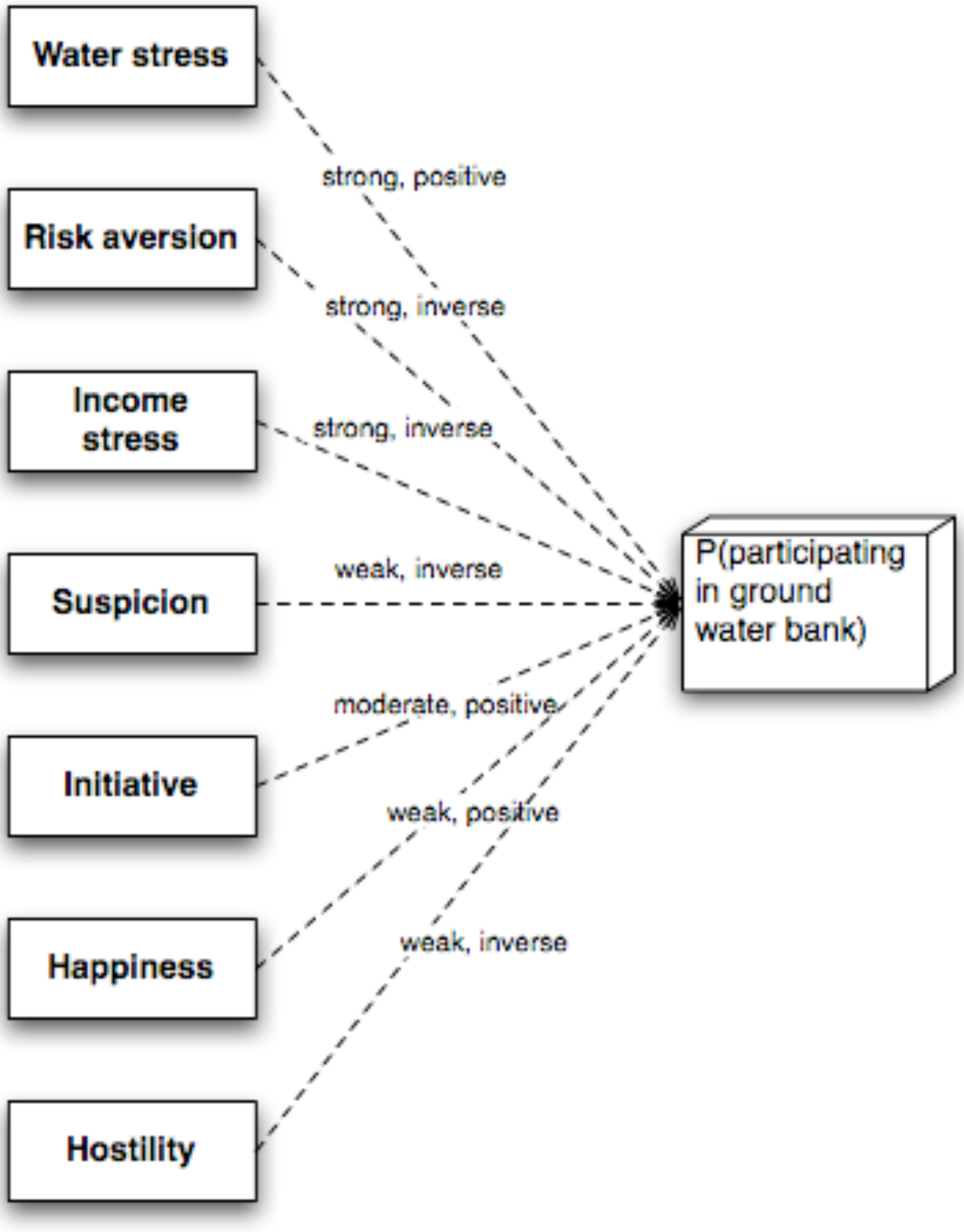


Figure 10: influence of emotional variables on the probability of a GWI agent participating in the bank. 'strong' in 'strong, positive', refers to one position along a spectrum of strengths of influence: weak, moderate and strong. A weak influence corresponds to a minor (<0.01) change in the probability; a moderate influence is a <0.1 and >0.01 change in the probability; and a strong influence is a >0.1 and <1 change in the probability, where all changes can be positive or negative. The 'positive' in 'strong, positive' describes the direction of influence: a positive influence for water stress indicates that when water stress increases, the probability of that agent participating in the bank will likely increase. An inverse influence for risk aversion indicates that when risk aversion increases, the probability of participation will likely decrease. Note that 'strong' versus 'weak' relationships effectively also determines the likelihood that the input

variable will have a significant effect on the output. 'weak' relationships may be lost in the general noise of multiple variables affecting one output variable or behavior, whereas a 'strong' relationship is likely to be observed over all others (i.e. agent behavior or internal state is more sensitive to these variables). But note that the large number of fuzzy patterns, and the large number of stimulus-response pairs, means that the full range of effects is not yet fully explored, and there may be unknown confounding variables and relationships poorly understood at this point (without comprehensive validation as yet complete). Figure 11 displays another sampling of input variables (some emotional, some non-emotional i.e. beliefs about the state of the world internally or externally), and which output decisions these are most likely to affect based on knowledge of the a priori structures in the code.

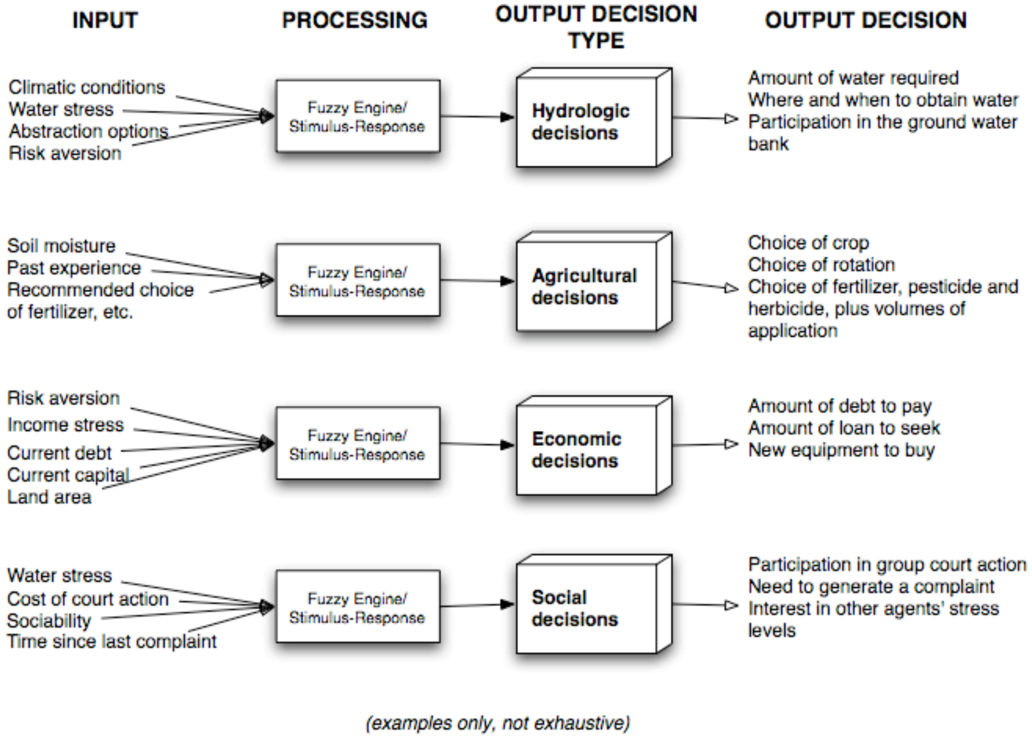


Figure 11: sketch of decision flows from input variables (emotional and non-emotional) through to output decisions. Note that the diagram does not specify exactly what the nature of the influence is, merely suggesting that – given the nature of the code – that there will be some form of likely relationship between the listed input variables and the listed decisions. Note also that this diagram is not exhaustive: due to space limitations, only a selection of inputs and outputs can be presented.

The choice of these emotional concepts versus others was drawn largely from the results of the interviewing work conducted in January 2007 (see Appendix for example questions). For example, it was clear (qualitatively) from the interviewing that there existed hostility (antipathy towards) surrounding the concept of the ground water bank. This gives us the variable 'Hostility', which – in general - determines the agent's likely mode of behavior towards other agents and towards the outside world in general. Some interviewees were clearly suspicious of the concept, particularly of the model that would be used to operate the bank. This gives us the ‘Suspicion’ variable, as well as the ‘Model Trust’ variable. This latter variable is a critical influence on repeat participation in the bank; once the initial choice is made, if the agent develops a reasonable level of trust in the bank, the agent’s trust in the model operating the bank will also develop positively. A low level of model trust will reduce the likelihood of the agent participating again in the bank the next time around. Note that all agents begin with a similar range of emotional states – the Latin Hypercube Sampling approach dictates that the emotional states across all agent types vary from run to run, but each agent experiences the same broad range of emotional variation over all runs. There were clearly some interviewees and stakeholders who had more initiative and creativity in terms of how they were responding to over-allocation and other hydrologic and economic crises in the eastern Snake. This gives us the ‘Initiative’ and ‘Apathy’ variables, which effectively control how ready the agent is to adopt new concepts (agents with high initiative are likely to be early adopters). Last but not least, interviewees clearly possessed some degree of happiness with the state of the system: this is a very generic term, similar in nature to the stress variables described earlier, but is a useful measure of the agent’s overall level of satisfaction. Agents generally do not directly aim to maximize happiness, although a reduced level of happiness is tied to increased stress.

The discussion here illustrates that the choice and implementation of emotional variables is, as yet, very simple, and clearly much remains to be desired regarding the sensitivity of the model to different emotions and the sophistication with which emotional concepts are represented. However, it was seen as essential to have some emotional component in the model: none of the stakeholders in the eastern Snake are economic automatons. All of them are complex individuals with diverse life histories and highly varied outlooks on the world. To pretend that emotions do not have a role in decision-making is to overlook a very significant component of human interaction and human thought. As Macal and North (2005) suggest, “Cognitive scientists are developing agent-based models of emotion, cognition and social behavior based on the notion that a person’s emotional state impacts their behavior as well as their social interactions… The goal is to create synthetic agents who embody the nuanced interplay between emotion, cognition and social behavior.” (Macal and North 2005, 6). However, the highly subjective, relatively coarse nature of the current implementation of emotions is acknowledged, and consequently the role of emotions is deliberately underemphasized; i.e., a change in a particular emotional state, even if the change is a significant one and the relationship between that state and a particular behavior is ‘strong’, the probability still remains low that the change will be enough to shift behavior, assuming everything else remained the same.

3.1.5 … Agent Learning

A small, yet important component of the simulation is the ability of agents to ‘learn’ from past experience. The learning is unsophisticated and far from what we might consider human learning to be, however it does represent an adaptive response to changing environmental conditions. The principal form of ‘learning’ that the cognitively active agents can engage in is behavioral modification through feedback. For example, if a decision one year leads to very poor yields, little water and a higher overall level of income and/or water stress, the agent will respond to this by shifting behaviors to minimize the negative impacts of its previous decisions and avoid them in future: the agent might seek to participate in the bank to obtain more water, choose a different crop (breaking out of rotation, if necessary) or go to the bank for more money. Each cognitively active agent is equipped with a simple memory which stores records of events and internal state for each month and each year of the simulation. Certain decisions – such as participating in the ground water bank, or choosing crops, or selecting loan request amounts – involve checking back in memory to see if the previous year's decision, or the year before that, was particularly bad and needs to be discounted from the options available. The agent does not search back more than a couple of years, which is a cognitive limitation identified from the stakeholder interviews undertaken in the region: several different sources, particularly from the academic community but even within the farming community of the region, suggested that farmers have a very short and selective memory for 'good' versus 'bad' years. The overall impression was that the typical farmer deliberately underemphasizes the bad years in memory, and overemphasizes the good years, and that either memory does not last for much longer than two to three years. In this way, a string of good years will likely lead the farmer to stop behaving in a way that is preparatory or mitigating of the potential for bad years in future. The probability of a bad year is still increasing, however, which demonstrates how humans do not optimize their decision-making! Consequently, agents are equipped with the ability, for certain decisions, to 'optimize' in a fallible way across the past three years of their experience: choose the best option based on the performance of previous choices in terms of the relevant output.

3.1.6 ... Treatment of Uncertainty and the Future

The agents do not plan for the future. No agent has any concept of future impacts of their actions, although all cognitively-active agents have some concept of the past impacts of their actions based on their memory. Agents tend to select the best option according to their limited (and short-term) learning from past experience, and the innate tendencies imparted to their decision-making by the base code. The risk aversion, initiative and curiosity emotions will drive more risky decision-making, but no agent factors in future uncertainty or future events to decision-making. This is a major and flawed assumption, since it was clear from the interviewing that the stakeholders do consider the future in an advanced, abstract way: for example, the trout farms are constantly gambling on the possibility that the water quantity and quality may decrease in future beyond the tolerance of the trout, whenever they make major investments in personnel and/or infrastructure. One exception to the general model rule of no 'forward-looking' ability in agents is the ground water user-specific variable, 'perception of future mitigation'. This is a belief which projects the likelihood that, at some point in the future, the SME will impose limitations on the amount of water that these agents can withdraw using their wells. Changes to this belief are, at present, very crudely controlled: a 'mitigation-likelihood' signal is communicated to all GWI agents each day by the SME, with the SME generating this signal based on the overall number of complaints and court actions so far received that water year. The perception of future mitigation is used in a similar manner to the risk aversion variable: a perception of more likely future mitigation will contribute to a greater agent willingness to participate in the bank and so offset that future mitigation, and vice versa. A second exception to the general model rule is the use of climatic forecasts. All farming agents receive a climatic forecast, the GWIs from the SME and the SWIs from their respective canal companies. The SME and CCs generate forecasts by taking a gamma distribution of the real historical precipitation and temperature data for the eastern Snake region. An arid forecast will influence agent behavior to be more conservative in water use and choice of crop; a wet forecast will generally have the opposite effect. Note that agents do not make longer term plans based on longer term forecasts as well as a consideration of past experience.

In summary then, agents treat the past and the future with some simplicity: past experience is only used with a three year time limit, and then only for certain decisions where the past is particularly useful (e.g. choice of crops, choice of loan request amount, and so on). Many other elements of agent decision-making is purely Markovian, since the next step may depend almost entirely on the previous step taken. For example, when it comes time to choose crops, the agent will check whether the current rotation is profitable enough and not too risky given the climatic forecast and the agent’s memory of previous water availability. This is an example of a reflective decision where memory played a role. However, the frequent decision point that forces the agent to decide whether or not to launch a court action depends mostly on the state of internal stress at that point in time, and not a set of conditions back in time. The agents treat the future with even less sophistication, apart from some specific variables – such as perception of future mitigation, and climatic forecasts – which are used in a Markovian fashion to determine the right decision from a selection of options.

3.1.7 ... Description of Agent Typologies

3.1.7.1 ... Irrigators

The irrigator agent typology in GWBSIM has a generic structure with modifications for two different subtypes of irrigator: ground water irrigator (GWI) and surface water irrigator (SWI). The core elements of both subtypes are the same, but the actual beliefs, desires and intentions/actions open to the agent are strongly determined by that agent's type.

The subtypes are based on real life distinctions: irrigators in the Eastern Snake tend to use ground water and/or surface water to irrigate their crops. For modeling purposes, these typologies are separated out into separate water uses, i.e. surface water users only use surface flows from the Snake River, and ground water users only use well water. Development of the basic economic, legal and environmental functions of each irrigator agent (e.g. buying fuel, launching a legal suit, spreading fertilizer) were implemented with general knowledge of how these actions are accomplished in the real world. More specific structuring and parameterization, such as the choice and relative weight of social and emotional variables, was conducted using interview data gathered in January 2007.

The differences in typology are primarily manifested through different sets of beliefs, desires, intentions and resources. A simple example of this is in the agent's use of beliefs and resources. A surface water irrigator is dependent on its annual allocation from the SME – the WaterRight and HeadgateFlow variables – variables which are critically important to its decision making. The ground water irrigator, on the other hand, has a water right that is pre-determined and does not vary year to year. The agent pumps as much as it can within its annual quota. There is no annual variation in the allocation unless the SME issues a curtailment order that has to be met by some form of physical mitigation. In this way, different agents make different uses of the same types of belief data. Another example is in the social capital of different agents: ground water users, perennially being blamed in the real system for causing surface water flow loss downstream, are represented in the model with less social capital than their surface water using neighbors.

Both Irrigator subtypes store some of their current beliefs, desires and resources data in variables representing long term memory. Long term memory is represented using custom-built *MemoryMap* data structures. These can be summarized here as simply providing for the efficient storage and retrieval of key-indexed information, and for the modification of key-indexed information over time. The key can be the year of storage, the type of information, or in fact any primitive or non-primitive data type the agent wishes to use. Similarly, the stored information can be as simple or as complex as the agent needs. An entire year's record of flow data can be stored just as easily as one day. Memory for each agent is generally updated once a year, and rarely comprehensively (an average or a median of numerical data is typically stored rather than an actual time series, both for purposes of realism and efficiency).

3.1.7.2 ... System Management Entity (SME)

The system management entity is an agent designed to represent a high level institution in the ESPA area, administering water resources allocation in the basin, and recording instances of conflict among agents. The internal cognition of the agent is on a much simpler scale than for the irrigator agents, because the SME has limited functionality and no need for complex reasoning capabilities, but the SME still possesses the thinking/doing loops described earlier. The core functions of the SME are as follows:

- *Records court actions by individuals or collections of agents*: the model allows individual agents or groups of agents to file suit against another on the basis of perceived injury in relation to reduced water allocation. For example, if a surface water irrigator finds it is short of its allocation for several years in a row, it may decide to initiate a court action against the nearest ground water irrigator. This court action process involves sending a message to the SME, which records the plaintiff, the defendant, and the deficit claimed as injury.
- *Sets up all agents with spatial and other initialization data*: the SME reads in data from the relevant databases and parameterizes all agents at the beginning of each simulation run. For example, the locations in the model animation space of each Aquifer cell needs to be drawn from a large table of row/column data

(derived originally from converting the lat/long values for the ESPAM 1.1 cells into the 0,0 Java-modified coordinates of the model animation canvas). The SME takes care of reading in these locations and making sure each Aquifer cell is apprised of its row/column data before being animated. The SME also handles parameterizations according to the LHS table (see earlier discussion).

- *Manages the ground water bank*: the SME conducts administrative functions that keep track of leases, deposits, bank volumes and determining harm/no-harm for a particular proposed transaction.

3.1.7.3 ... Market

The Market agent is another simple agent designed to hold globally-accessible economic data for use by irrigator agents. For example, the Market agent records current crop prices for potatoes, wheat and corn; fuel costs for machinery operation; machinery purchase costs, and other economic data. These datasets are simple lookup tables that individual agents can access at any point.

3.1.7.4 ... Canal Company (CC)

The CC is a simple agent with no active cognitive functions. The Canal Company's principal role is to distribute water from its canal system to those SWIs that are members of the canal and so are holders of a certain water right in that canal. For example, SWI #45 may hold 245 shares in CC #2. The CC determines what each share is worth (perhaps 0.01 cubic-feet per second), and distributes the equivalent volume of water to that shareholder (in this case, 2.45 cfs). The model distribution process is approximately similar to that occurs in the real world: the canal company does not deliver a 'parcel' of water to the agent, but simply notifies that agent of the availability of that water and for how long it is available. The agent will then make use of that amount of flow until the flow in the canal changes, ends or the agent is asked to shut its lateral headgate by the canal company. The CC agents also take care of mediating between the River/Aquifer agents and the individual irrigators: return flows and diversion values from individual irrigators are summed and passed onto the Reach, River and Aquifer agents in order to couple the environmental actions of individual agents to environmental effects.

3.1.7.5 ... Reach, river and aquifer agents

These are non-cognitive, purely functional environmental agents. The Reach agents are the principal points of interaction for the ground water bank and for simulation of the river flow. Reaches 2 through 10 of the 11 reaches have upstream and downstream neighbors with which they interact - passing water according to flow rates and other characteristics of each Reach. Reach 1 receives an inflow at a rate according to USBR Hydromet historical data), and Reach 11 passes its flow to a sink outside the model realm. Each Reach cell also may receive updated flow data according to the positive or negative effects of a particular ground water banking activity, and certain Reach cells receive inflows from tributaries roughly corresponding to the real world position of actual tributaries. River agents are created simply for the purpose of providing an animation of each river cell on the model animation space, but perform no functional role. Aquifer agents take care of calculating and propagating the effects of ground water pumping. Note that while this approach to simulating the Snake River is not the most appropriate or the most valid, it does represent a considerable time savings over the MODSIM-coupling option, and does a reasonable job of reproducing typical annual variation in Snake River flows

3.1.8 ... GWBSIM ground water bank

Under GWB, the aquifer is conceived of as a water bank. Agents can make deposits and withdrawals at will, but are constrained within a number of coded rules. These are as follows:

Quantification of transactions: all deposits and withdrawals are quantified in terms of the net acre feet of depletion or recharge that each causes. For deposits (recharge), this is the amount of water that is recharged, discounted by a 5% 'uncertainty allowance': “this protects other users of the aquifer from distortions caused by imprecision” in the hydrological modeling (Contor pers. comm. 2007). for withdrawals (pumping), this is the total amount of water pumped (Contor pers. comm. 2007).

No Harm Rule: no deposit or withdrawal is permitted if the local Aquifer agent finds that the transaction would result in damage to surface water reaches. This would occur if the pumped amount exceeded the original deposit multiplied by its decay function, or the withdrawal exceeded the threshold of influence on the aquifer and river such that reaches were affected.

Shrinkage and cost of transactions: each agent has the option to deposit or withdraw water from the aquifer at the end of each time step: the withdrawal costs money at a price set by the SME. All deposits made by an agent are modified over time by a discount rate which corresponds to a shrinkage of the resource underground: as Contor points out, the primary shrinkage mechanism for a body of water stored in an underground aquifer is the migration of water into other hydrologically-connected water bodies. Consequently, water stored in a bank is not static, and a certain proportion is lost to the system between the time of withdrawal and the time of deposit.

Withdrawals: ground water bank water can be withdrawn out of priority (i.e. out of the normal priority allocation process associated with surface and ground water rights) due to the fact that the water would not have been there if it were not for the GWB process, and so is assumed to be outside of the prior appropriations doctrine.

Management of the bank: the SME manages the deposits to the bank, issuing each depositor with a 'certificate' for the deposit. The certificate records the amount of the deposit and the specified decay function for the deposit. The decay function defines how much the deposit is worth at some time in the future. Pumping with a prior deposit is free as far as the certificate (and associated decay function) states that this amount of water is still available in that portion of the aquifer for use by the agent. Effects of agent withdrawals or deposits are calculated by the SME using gamma distributions of the response functions derived from the ESPAM 1.1. This data is used to determine the harm (or no harm) of a particular transaction. The 'real' response functions, unmodified, are used by the Aquifer agents to propagate the effects on surface water reaches of any pumping or deposit activity by an agent. In this way, the distinction between modeled and 'real' effects that a real world bank would have to deal with is reproduced in the simulation environment.

Participation: Only SWI and GWI agents can participate in the bank - GWIs can both deposit and withdraw, but SWIs can only deposit.

3.2 ... AlbAgent specification

3.2.1 ... Environment

The AlbAgent environment is divided up into land and water components. Each farming agent owns a parcel of land, which is defined in a model as a separate class that itself encapsulates crop objects. When an agent chooses to plant a certain crop, the land parcel instantiates a particular crop object. Crop growth is not directly simulated, but a probabilistic method is used based on existing historic data and some broad assumptions about crop dynamics. The Land section describes both the land parcel concept and the simulation of crop growth. The water component of the environment is a 5135 cell aquifer based on a simple bathtub model (Figure X). Each cell has a volume of water associated with it, and a level of water in the cell defined from universal datum. The Water section below describes in more detail how the hydrology of the system is implemented.

3.2.2 ... Land

The *LandParcel* class, which each Farmer agent instantiates one copy of, holds terrestrial environmental information relevant to the Farmer's production of crops. Figure 12, class diagram for the *LandParcel* class, provides more detail (but for ease of viewing does not include all fields).

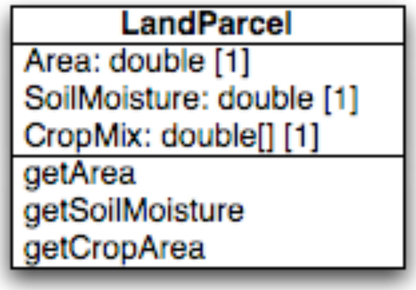


Figure 12 (right): simplified class diagram for the LandParcel class

The *CropMix* field describes the relative proportions of different crop types on the land parcel. Each array index corresponds to a particular crop type, as defined in a common reference table. For example, a 0.6 value in *CropMix*[0] would correspond to 60% of the Area devoted to cereal crops. The *getCropArea* method returns the actual area planted with a particular crop. The *LandParcel* class also takes care of crop yield simulation: the volume of a particular crop generated after that crop's growing season. This is accomplished via a simplified crop growth equation.

Equation 1: simplified crop growth equation

$$y = Ay \cdot WIp \cdot Sf \cdot Hc$$

where

y = yield (economic units)
Ay = average yield of crop type per hectare, from arid region agriculture literature
WIp = water application during growing season as proportion of ideal application
Sf = shock factor - pest infestations, frosts, etc (value of 0.0 = maximum shock factor, 1.0 = zero shock factor)
Hc = total active hectares for that crop

While being far from a credible simulation of crop growth, the equation is intended to reflect the strong influence of both water and external events (shock factors) on a farmer's yield. Equation 2 below illustrates the crop growth equation with a simple example:

Ay = 200 trees per hectare, 15 kg olives per tree average yield
WIp = water applied per tree 2.10E-3 hm, ideal application per tree 2.99E-3 (Fernandez and Moreno 1999)
Sf = 0.95
Hc = 322

$$y = 3000 \cdot \frac{2.1E\text{-}3}{2.99E\text{-}3} \cdot 0.95 \cdot 322$$

$$y = 644538.46\ kg$$

Equation 2: crop growth equation with inputs

3.2.3 ... Water

The hydrogeology in the study area is conceptualized as a single-layer aquifer with no-flow boundaries on all sides, i.e. there is no communication between the study area aquifer zone and any adjoining zones in the same or other local or regional scale aquifers. The aquifer is divided into a grid of cells (116 by 120 cells of side 1000 m) which fit within the study area (see Figure 13). Aquifer transmissivity is assumed to be equal in all directions, such that responses to withdrawal or injection in any area of the aquifer are propagated across the aquifer in a zone of influence of increasing magnitude. Data from

Sanz et al (2006) suggest that transmissivities in the UH2 Miocene aquifer unit underlying most of the study area range between 200 and 6000 m^2/day. Transmissivities for all aquifer cells are equal, a mean of 3100 m^2/day (Santos et al 2006). Equation 1 below illustrates the Theis equation used to derive a drawdown at some distance r from a pumping well, some time t after the original pumping event.

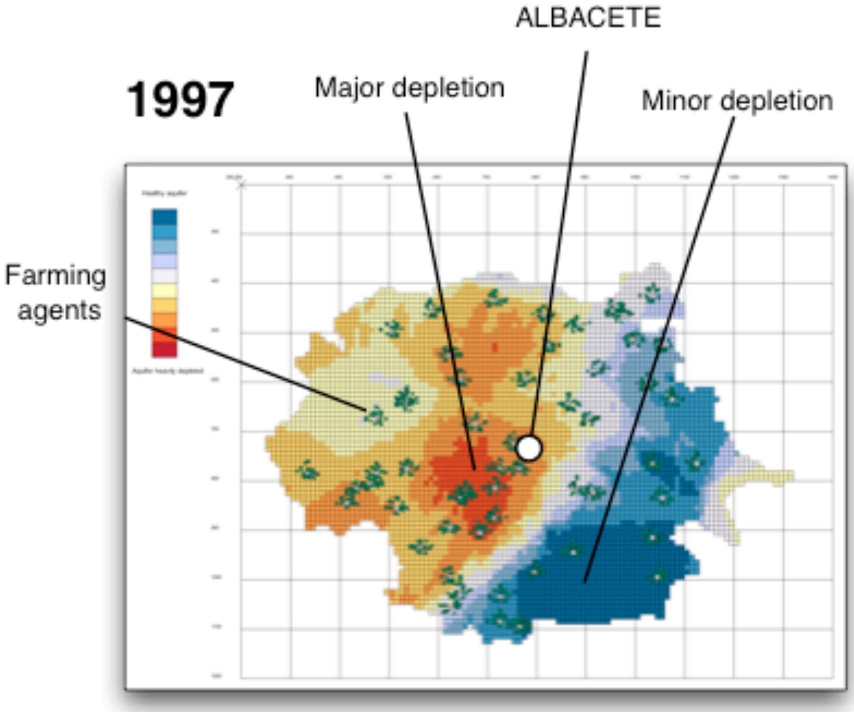


Figure 13 (right): diagram of study area grid at beginning of simulation time in 1997; scale across grid is approximately 110 km; grid lines are parallel to N-S, E-W directions

Equation 3 (below): Theis equation used to compute aquifer drawdown

$$s = \frac{Q}{4\pi T} W(u)$$

where

s = drawdown from original aquifer levels

Q = pumping rate

T = transmissivity, assumed for this region as 0.017 m^2/s

$W(u)$ = Theis function (drawn from Kresic 2007)

The Theis function is calculated based on the dimensionless parameter u:

Equation 4: calculation of dimensionless parameter u

$$u=\frac{r^2S}{4Tt}$$

where

S = Storage coefficient, assumed to be 0.2 (unconfined aquifers typically range between 0.1 and 0.3)

t = time since original pumping event

W(u) is calculated from u via an exponential integral (Krecic 2007):

Equation 5: Krecic's integral to calculate Theis function

$$W(u) = -E(-i) = -\int_{u}^{\infty} \frac{e^{-u}}{u} du$$

which was used in the example detailed in Table X to generate a series of W(u) values for each successive time step and Moore neighborhood (Table X).

t	Distance from cell 0	W(u)
0	**500**	5.4167
1	**1000**	4.7261
2	**2000**	4.0087
3	**3000**	3.6374
4	**4000**	3.3547
5	**5000**	3.1365
6	**6000**	2.9591
7	**7000**	2.8099
8	**8000**	2.6813
9	**9000**	2.6813
10	**10000**	2.4679
11	**11000**	2.3775
12	**12000**	2.2953
13	**13000**	2.2201
14	**14000**	2.1508
15	**15000**	2.1508
16	**16000**	2.0867
17	**17000**	2.0269
18	**18000**	1.9711
19	**19000**	1.9187
20	**20000**	1.8695
21	**21000**	1.8229

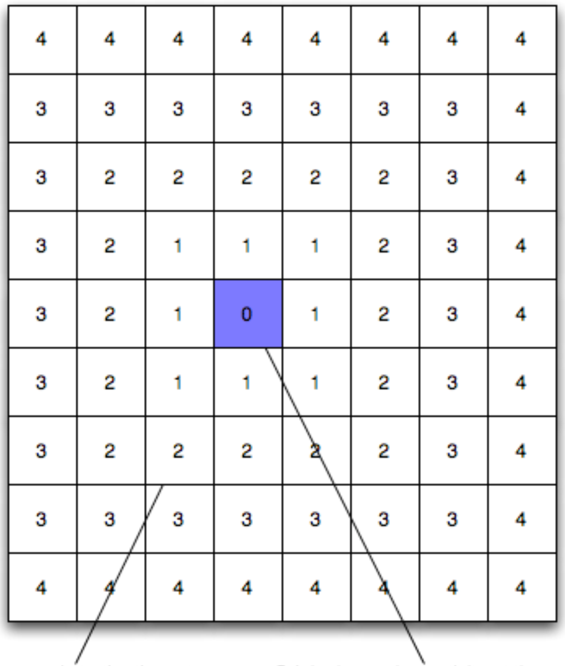
t	Distance from cell 0	W(u)
22	**22000**	1.8229
23	**23000**	1.8229
24	**24000**	1.8229
25	**25000**	1.8229

Table 1: table showing Theis functions for cells at distance n from cell 0

The immediate drawdown in the pumping cell is calculated using equation 1 and a value of 500 m for r (distance from the pumping location). Wells are located at the center of cells.

The effect of pumping at any one cell is calculated for all other cells on a temporal basis: cells in the immediate Moore neighborhood of the pumping cell have the effect calculated using equation 1, one time step after the original pumping event. Two time steps after the event, the neighborhood is expanded (see Figure 14 below) and the effect calculated again. This is intended to convey, in simplistic fashion, the delayed response of a large aquifer to a particular pumping event. Note that a single pumping event is, for ease of modeling, defined as a single 10 hour event that happens instantaneously in a particular model time step. For the example below, one time step after the application in each successive Moore neighborhood, the cells in any one neighborhood see their water level stabilize at 249.9996 m above datum, assuming a study grid area of 13456000 m^2, a withdrawal of 5040 m^3 (10 hours of pumping at 0.14 m^3) and no other pumping events in the intervening period. However, it is likely that, by the time a single pumping event propagates to the edge of the grid, other pumping events will also have occurred. To handle this, each event is distributed in effects across all cells, with a time stamp of future activation (e.g. for the 18th Moore neighborhood, the 18th time step after the original event). Each cell will likely build up a queue of pending effects, and these are implemented when the actual time step matches the effect time stamp.

Figure 14 below shows an example of the effects of withdrawing water at a rate of 0.14 m^3/s from a central cell during a 10 hour pumping event. Since it is assumed that the aquifer is unconfined and there is no interference between cones of depression, the lag rate (rate at which ground water levels equilibrate is assumed to be instantaneous, 1 time step after the application of a pumping event. This has the effect of all cell ground water levels decaying to a system-wide height above or below the pre-pumping water level.



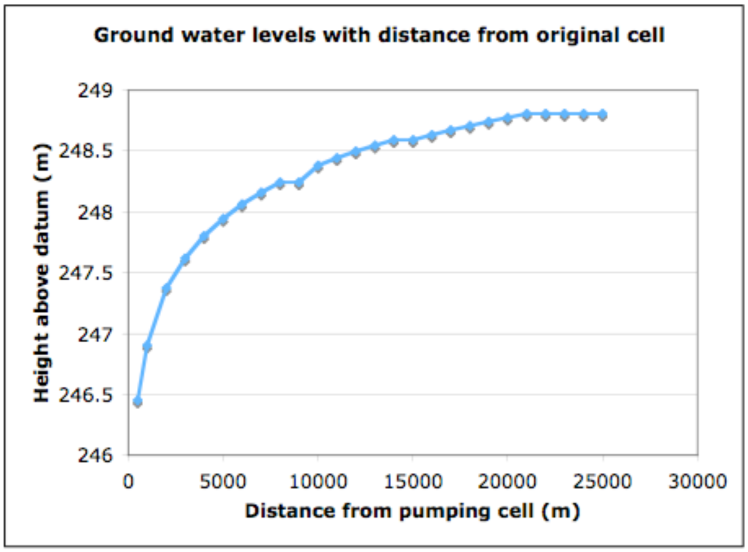
4	4	4	4	4	4	4	4
3	3	3	3	3	3	3	4
3	2	2	2	2	2	3	4
3	2	1	1	1	2	3	4
3	2	1	0	1	2	3	4
3	2	1	1	1	2	3	4
3	2	2	2	2	2	3	4
3	3	3	3	3	3	3	4
4	4	4	4	4	4	4	4

Number corresponds to the time steps after the original event when the cell experiences an effect due to pumping

Original pumping activity at time = 0

e.g.

Assumptions for Theis equation
Original pumping event = 0.14 m3/s
Original head in well (and all other cells) = 250 m AD (above datum)
Transmissivity = 0.017 m2/s
Pumping time = 10 hours
Volume lost from system = 5040 m3
Storage coefficient = 0.2
W(u) from Keric (2007)



Graph shows drawdowns from original 250 m head levels across all cells, one week after the pumping event (= 1 time step)

Figure 14 (above): diagrammatic illustration of Theis equation

Although for ease of modeling the system is conceptualized as closed, the aquifer does have external inputs. These are defined as follows:

Precipitation: direct infiltration from precipitation-sourced runoff; the annual precipitation data for the Jucar basin is averaged across the study area, and assumptions made as to the rate at which water moves into the aquifer. According to Ferrer-Julia et al (2002), medium-scale kriging across northern Albacete returns estimates for soil infiltration at 20 to 100 mm/hr. Noting the karstic nature of the terrain north of Albacete, the upper quartile of the range is sampled for typical infiltration rates over the study area: 80 to 100 mm/hr. Martin-Rosales et al (2006) suggest that "recharge processes [in arid regions of eastern and south-eastern Spain] are intimately linked to episodic events" (Martin-Rosales et al 2006, 1). Consequently, recharge events are simulated with an infrequent arrival rate derived from a Poisson distribution.

Return flow: direct infiltration from irrigation activities by Farmer agents; in the absence of detailed datasets, and for ease of modeling, aquifer recharge rates (proportion of water applied that returns to the aquifer) for any one aquifer cell are drawn from a truncated normal distribution, mean of 0.3, standard deviation of 0.05 (based on estimates for climatologically and geologically-similar regions; Gates et al 2002; Doble et al 2005).

River losses: infiltration through the stream bed of the Jucar and other stream and river systems inside the study area; given the low flows in the Jucar and other tributaries, this input to the aquifer is not simulated.

Inter-aquifer connectivity: there is undoubtedly communication between the study area region of the UH2 aquifer unit, but for ease of simulation and due to data inaccessibility subsurface movements of water into and out of the aquifer are not simulated.
River systems: the principal contribution to irrigation supplies in the Albacete region is the aquifer, and local or regional river systems are not simulated.

3.2.4 ... AlbAgent agents

Much as for GWBSIM, the agents are described first in conceptual and then in more technical terms. The specification is somewhat less detailed than for GWBSIM, however, since the AlbAgent model is a great deal less complex.

3.2.4.1 ... Conceptual description of AlbAgent agent typologies

Only two typologies are represented in the system: the Farmer agent and the CHJ agent. The Farmer agent is loosely based on the dominant farmer type in the Albacete region: a farmer growing mixes of cereals, fruits, olives and vines using groundwater-sourced irrigation. A small proportion of some agents in some scenarios grow *secano* (non-irrigated) crops, but there is no difference in the internal structure of those agents. The CHJ agent is loosely based on the Confederacion Hidrologica del Jucar, a regional-level body which is responsible for managing irrigation allocations, hydraulic infrastructure (canals and dams) and hydrologic data collection (not an exhaustive list). The agent is represented as a non-spatial, non-reasoning agent with certain regulatory responsibilities that it fulfills regardless of the internal or external states of the Farmer agents. The CHJ does respond to the condition of the aquifer, since in the more severe institutional change scenarios (see later discussion of scenarios) the CHJ will aggressively limit Farmer agent usage of water if the conditions in the aquifer reach a certain level of depletion.

As discussed above, the Farmer in AlbAgent corresponds loosely to the GWI or SWI agents in GWBSIM. As in Idaho, the agricultural trend in Castilla-La Mancha is towards larger and more industrialized farms, and so the Farmer agent is loosely oriented towards larger scale, profit driven agriculture. Unlike Idaho, the Albacete region has very little surface-sourced irrigation due to its higher aridity and the karstic geology. This necessitated a paring down of the Farmer typologies to just a single, ground water using type. The Spring Users of GWBSIM have no counterpart in the Spanish setting, and so were also not replicated. The municipality of Albacete, the regional government, the irrigation community in Alicante, and the national Spanish government are all additional possible agents that were not simulated. For most of these, it was a boundary decision which kept the overall model as simple as possible. In the case of the municipality of Albacete, the city's hydrologic role was assessed and deemed insignificant except as a consideration for the CHJ agent. Indirectly, the city has a very powerful role. It is widely assumed that agriculture will not have the final vote on water use in the future - if water quality and quantity decrease to the extent that domestic use is being restricted or otherwise adversely impacted, regional experts suggest that immediate and widespread agricultural water use restrictions would come into play (Angelo 2007, pers. comm.). Acknowledging this reality, the CHJ is equipped with a trigger to implement various water restriction policies on the farming community once aquifer and climate conditions go past a certain point.

Before discussing both typologies in more technical detail, Figure 15 below specifies the overall structure of the model.

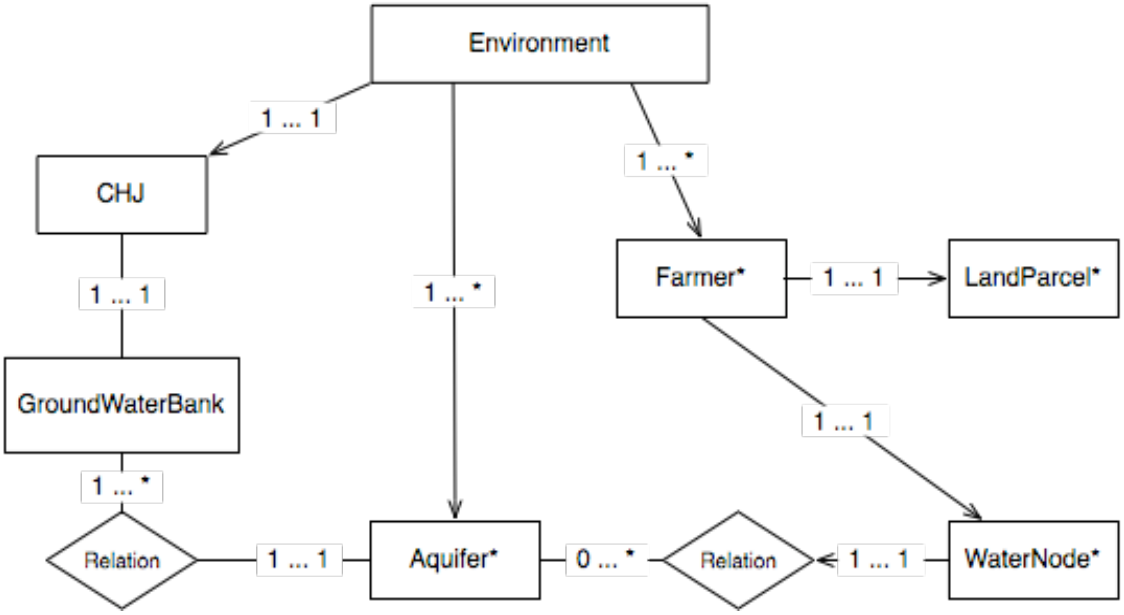


Figure 15: major entities in the model. The 'Environment' entity is a wrapper provided by the development platform (AnyLogic) which consists of a number of arrays corresponding to the number of different active agent types. For example, environment.Farmer is an array holding all the instantiations of the Farmer class in the model. A relation is an indirect (non-encapsulated) linkage between two classes. For example, each Farmer agent encapsulates a WaterNode, which has a reference to the aquifer cell nearest to the agent, and each Aquifer cell may have 0 or many references to the WaterNodes referencing that cell. Each Aquifer cell has a direct reference (one to one) with the GroundWaterBank, but the GroundWaterBank references many Aquifer cells.

3.2.5 ... Technical description of AlbAgent agent typologies

3.2.5.1 ... Farmer

The Farmer agent is a generic typology; different 'flavors' of Farmer are based on the same basic class, with modifications of key fields. For example, farmers focusing on different crop types are differentiated on that basis. From the 1999 Agricultural Census, the core agricultural types in the Albacete locale are:

Cereals
Fruit
Olives
Vines

The Farmer superclass structure is illustrated in Figure 16 below.

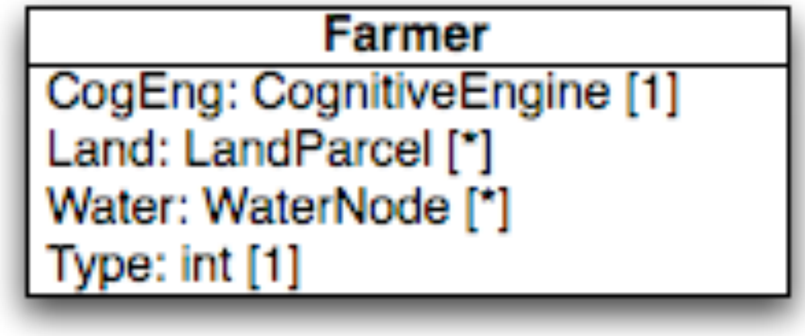


Figure 16: class diagram for Farmer class in AlbAgent

The CognitionEngine, LandParcel and WaterNode classes are described under the Cognition subsection below. The Type field can take on any integer value between 0 and 3, corresponding to the principal crop type listed above. In exceptional cases, the agent begins with a parameterization of Type 4 (secano, or non-irrigated crops). In most scenarios the agent can also switch to non-irrigated crops if it so chooses. In the present version of AlbAgent the farmer is restricted to farming one type of crop for the duration of the simulation.

3.2.5.2 ... Farmer cognition

Farmer cognition is accomplished using a simplified BDI model (Belief-Desire-Intention; Rao and Georgeff 1995), very similar to that adopted in GWBSIM. Some important differences in technical implementation are discussed below, but the overall cycle of thought and action, shown in Figure 17 (reproduced from above), remains the same.

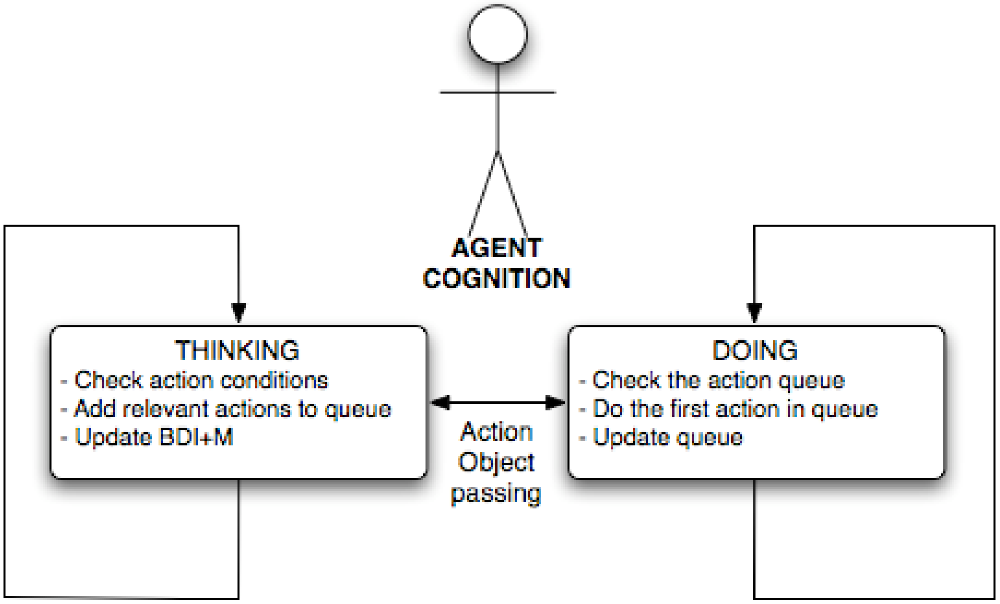


Figure 17: cycle of thinking and doing implemented in AlbAgent

A key technical difference is that the process of converting beliefs and desires into intention and action has been made conceptually more precise, with additional classes implemented. AlbAgent Farmer agents process '*Temporal Tag*' '*Concept*' and '*Intention*' objects into '*Action*' objects in two continuous state chart cycles (Figure 18) that incorporate successively more detailed and specific filters.

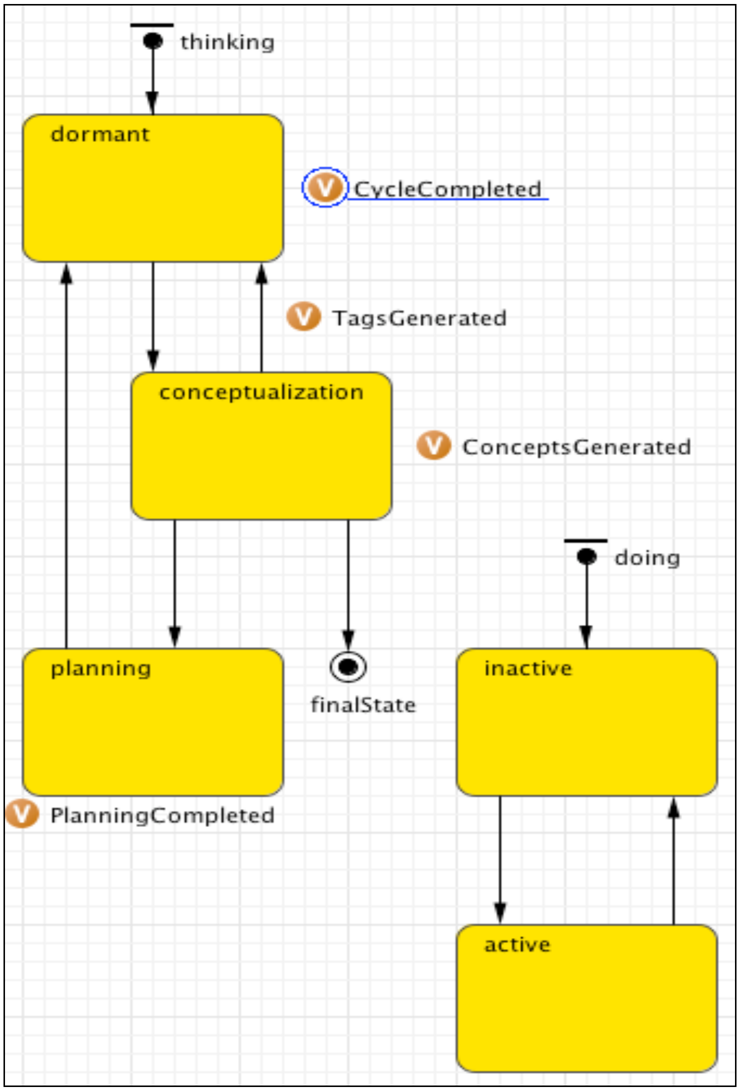


Figure 18 (right): screenshot from the agent-based modeling tool, AnyLogic, showing the statecharts for 'thinking' and 'doing' cycles of agent cognition

In the first transition of the 'thinking' state chart (from state [dormant] to state [conceptualization]), broad temporally-specific typology Strings are generated that correspond to a library of scheduled general activity groups (e.g. post October 1, "Irrigation" is a temporal tag String that becomes current, since the water year has begun). This provides a very crude first level of organizing all the possible intentions that agent could in any one particular time step. For example, it might allow the agent to immediately ignore any concepts, intentions and actions that involve harvesting, since the time of year is not appropriate to harvesting. While this does reduce the flexibility of the agent and the extent to which it can ‘wander off cognitively’, the approach considerably reduces the computational load presented by an agent.

Using these general temporal Strings, objects of class Concept are matched depending on whether the Concept object tags match the original String. A concept is essentially defined as a more specific grouping under the temporal tag (see also definition below). To make the description of these initial steps a little more concrete, here is an example set of steps:

1. Agent checks model time: February 3, 1998;
2. Agent searches a String-by-schedule library for basic temporal tags active on or after this particular date. In this case, we have 1 match - “Irrigation”;
3. ArrayList<String> created, with the tag String added;

State [conceptualization] of the cycle finds any Concept objects (in a second library of objects) with internal tags matching the temporal tag String(s). Continuing the previous example:

4. 2 matches are found (Match1 and Match2);
5. The agent checks the internal tags on each Concept object to determine its type. e.g. Match1.Tag = “Hydraulic”; Match2.Tag = “Economic”. These correspond to hydraulic and economic activities associated with irrigation. A hydraulic activity might be opening or shutting a headgate, whereas an economic activity might be buying more irrigation equipment or buying water.

In state [planning], the agent generates an ArrayList of Intention objects that have internal tags matching filtered Concept objects. Note that Concept and Intention objects are differentiated on the following basis: Concept object = general class of activities open to the agent under a particular temporal tag, e.g. economic, hydraulic, social; Intention object = less general aggregation of activities falling under a particular Concept, e.g. under the hydraulic Concept and the “Irrigation” temporal tag we might find OpenHeadgate, ShutHeadgate, RunPump, ShutOffPump). Continuing our example:

6. agent finds Intention matches with Match1.Tag: Intention objects with tags “OpenHeadgate”, “ShutHeadgate”, “RunPump”, “ShutOffPump”; and the same for Match2.Tag: Intention objects with tags “BuyWater”, “SellWater”;

Still within the state [planning], the agent feeds each Intention object through the central planning engine within the CognitiveEngine object. The planning engine runs a set of condition checking methods associated with each Intention, to assess the relevancy of that particular intention given a number of internal and external environmental conditions (varying depending on the Intention).

This filtering of Intention objects is accomplished by the ActionFilter class, and proceeds through a number of separate conditions that assign positive, negative, neutral or zero weights. If the resultant sum of the weights exceeds an archived threshold (which can be modified if necessary), then the Intention object is used to generate an Action object which is passed to the second state chart ('doing'). Figure 19 below excerpts some code from the development platform illustrating a set of conditions for the lease intention.

```
public Integer lease(){
int greenlight=0;
if ((Double)IR.getR(rs.TrustInBank) > (Double)IR.getP(rs.TrustInBank, rs.MIN)){
applyWeight(2);}
else { applyWeight(-2); }
if (Goals.isCurrentGoal(MethodCallTrace.Trace())) { applyWeight(2); }
if ((Double)IR.getR(rs.WaterAvailability) <
(Double)IR.getP(rs.WaterAvailability, rs.MIN)){ applyWeight(1); }
if ((Double)ER.getR(rs.GovtLeaseReqmnt) > 0.0) { applyWeight(1);
if ((Double)IR.getR(rs.TrustInGovernment) <
(Double)IR.getP(rs.TrustInGovernment, rs.MIN)) applyWeight(-1);}
if ((Double)IR.getR(rs.Risk) < (Double)IR.getP(rs.Risk, rs.PREF))
applyWeight(2);
else { applyWeight(-2); }
Weight = checkRemainingEvents(MethodCallTrace.Trace(), Weight);
if (!Account.canGenerateNewApplication(CurrentDate)) { applyWeight(0); };
if (!(Boolean)ER.getR(rs.BankingAllowed)) { applyWeight(0); }
if (has(rs.Lease)){ applyWeight(0); }
if (Weight>ActionThresholds.getThreshold(MethodCallTrace.Trace()))
{
greenlight=1;
}
Weight = 0.0;
return greenlight;
}
```

Figure 19: code from class ActionFilter: the lease() method is called when an Intention object with a matching tag is fed through the CognitiveEngine. Note that positive (applyWeight(+)) and negative (applyWeight(-)) weights can be applied to the overall weighting for the intention. The overall weight can be zeroed out if necessary (in this case, the weight is zeroed out if the agent has already leased, since only one lease is allowed per simulation year).

To continue our example from above:

7. Intention object with tag "OpenHeadgate" returns true for testActivation()
8. Planning engine generates Action object, tag "OpenHeadgate", adding it to the Actionable queue.

As soon as any Action objects appear in the Doing loop, the loop is activated. The loop grabs the top Action object in the queue (FIFO), and activates the action method in the agent's internal memory that corresponds to the Action object's tag. This is done without any further condition checking.

This dual cycle forms the core of all agent cognitive and environmental activity. The intent of the multiple levels of temporal and conceptual filters is primarily to reduce the need for a more detailed and processor-intensive cognitive cycle, by conducting a near-binary search of the tree of options that the agent faces each time step. It differs from GWBSIM in one particularly important area: in AlbAgent, new temporal strings, concepts and intentions can be added to a text file prior to runtime, without any additional coding. Some programmatic changes would be needed to make available the action associated with the intention, but the parameters and thresholds of selecting the intention can be set by anyone in the associated, reasonably self-explanatory text file. Figure 20 below illustrates the broad overview of the agent cognitive cycle as it has just been outlined.

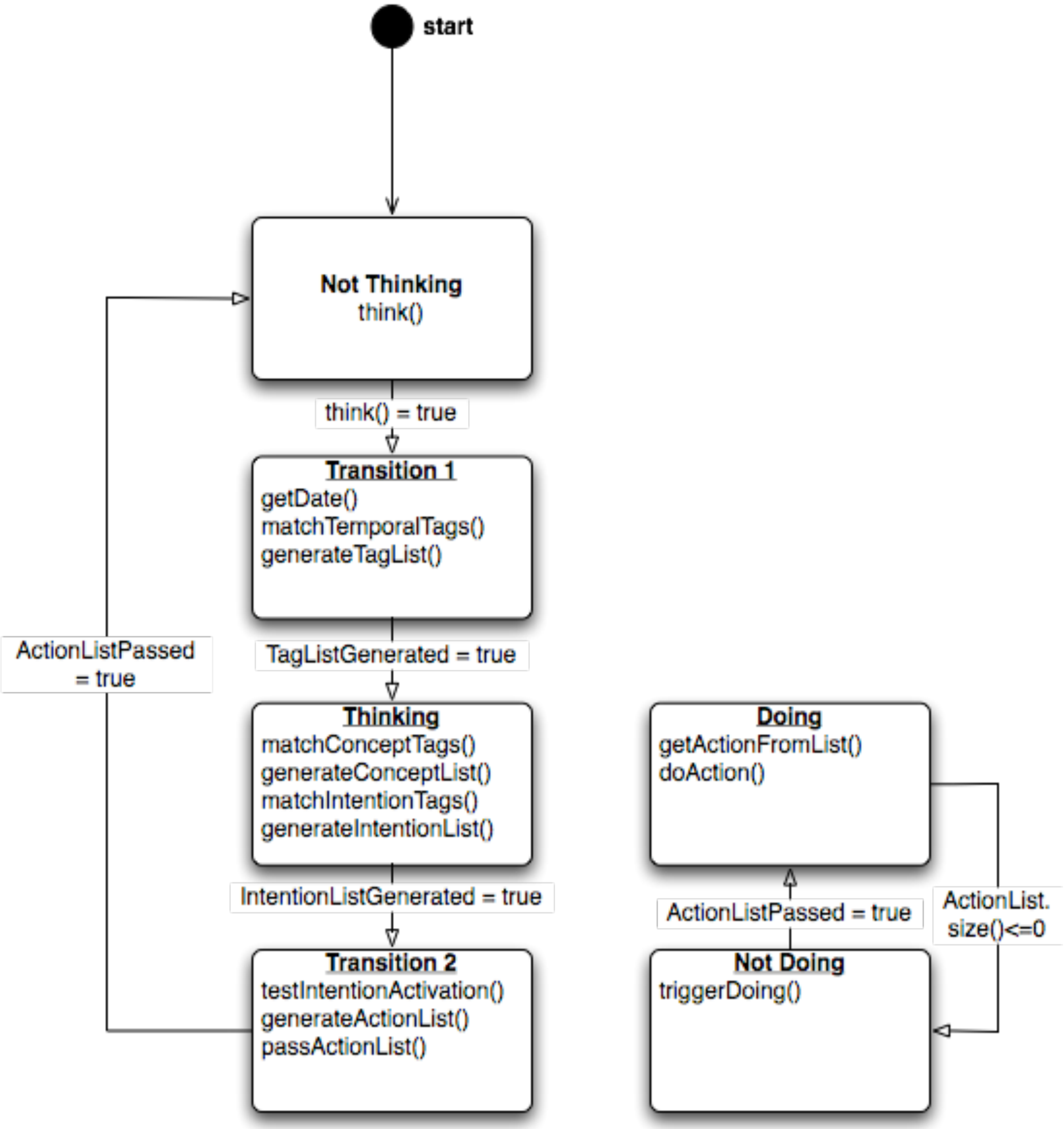


Figure 20: more detailed overview of the agent cognitive cycle, including real method names

3.2.6 ... AlbAgent agent communication

Farmer agents can communicate with fellow agents of type Farmer in two scenarios:

- **Information seeking**: agent 1 seeks some information about the internal or external environment of agent 2, e.g. agent 1 wishes to know how satisfied agent 2 is with a particular crop price, or, agent 2 wishes to know how much money agent 2 made last year.
- **Cooperation request**: agent 1 seeks the help of agent(s) 2...n for some task.

The following rules apply to communications of type 1:

- The target agent does not have to respond to a request for information from the source agent, and does not have to give true information in answer to the request;
- Agents are only allowed to send one information-seeking message per model time step.

The following rules apply to communications of type 2:

- The target agents do not have to respond to requests for cooperation;
- Any responses to cooperation requests must be made within 1 model time step of the request being received.

3.2.7 ... AlbAgent agent memory

The Farmer agent memory is implemented using the *Memory* and *Chunk* classes. The class diagrams for these are shown in Figure 21.

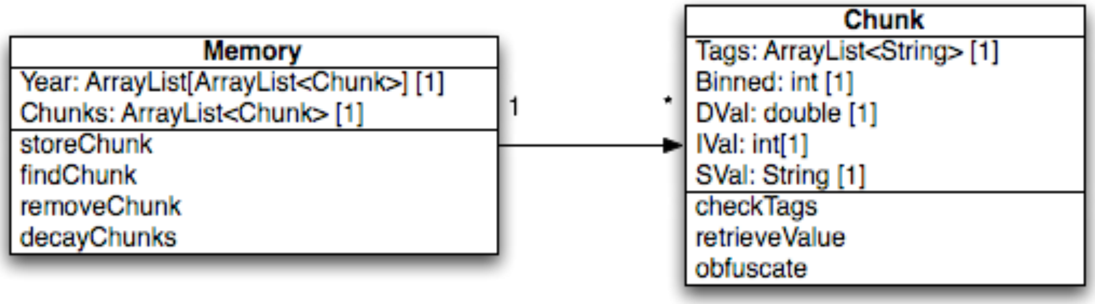


Figure 21: Memory and Chunk class diagrams

Each entry in the Years array holds an ArrayList containing a number of *Chunks*. Each *Chunk* has a number of tags associated with it, describing what kind of information is held in the Chunk's value 'bins' (the *DVal*, *IVal* and *SVal* primitive types). For example, a particular *Chunk* might hold "*Hydraulic*", "*River*", "*Flow*" tags, corresponding to steadily refined levels of classification. The *Chunks* are accessed by agents through a particular year. e.g.

1. *Memory* query: what was the river flow last year?
2. *Tags* parsed from the query: "*flow*", "*river*"

3. Last year = 1997
4. Years[0] contains 3 *Chunks*, the second of which has both “*river*” and “*flow*” tags.
5. The *Binned* field lets the querying agent know which of the bins holds the relevant value, in this case *DVal*.
6. DVal = 34.23 is returned to the original query.

Additional functionality is provided by the *storeChunk*() and *removeChunk*() methods. The *obfuscate*() method in class *Chunk* is designed to replicate a function of human cognition, the blurring of numerical values in human memory the more frequently the number is accessed. As the *Use* variable increments, the P(*obfuscate*()) increases. The method will find the stored value and modify it by some amount within 10% of the original value, e.g. the 34.23 flow value is changed to 32.21. The *decayChunks*() method in class Memory takes a more drastic approach to simulating the fallibility of human memory, by randomly removing chunks. Chunk removal is undertaken infrequently according to a Poisson distribution.

Note that, as for GWBSIM, no agent has a true conceptualization of the future - such as a dedicated cognitive mechanism for handling long term implications of actions. There are isolated, hard-coded instances of taking account of the potential future: most Farmer agents are made ‘aware’ that the CHJ could take some action in the future to reduce some or all of the water use by the Farmer agents. The extent to which an agent fears that outcome is encapsulated in the *FearOfGovernment* internal resource (see discussion of resources, below). In reality, the value of this resource is controlled by an in-built cognitive loop that increases the fear of government action as more time goes by and nothing has yet been done. Like all internal resources, the actual value of each resource will vary by agent, since the amounts by which each variable increases or decreases in response to an external variable is distributed in either a uniform or gaussian manner. Some additional potential variation is built in, since agents can and routinely do ‘check in’ with their neighbors to see what they ‘think’ about something (i.e. query the state of some internal resource of a neighbor). Agents can also (and routinely do) start rumors of government action, which are passed around a fixed number of agents before disappearing. The potential for highly organized behavior that can result from such simple rules is one reason why this particular setting is so ripe for agent-based modeling.

3.2.8 ... AlbAgent agent learning

The learning component of agent cognition is confined to a simple stimulus-response mechanism. If particular *Action* objects recurrently lead to reduced welfare or satisfaction on the part of the agent, the base activation level of the object is reduced so that - even if conditions appear to be right for that action - it becomes less likely the action is taken.

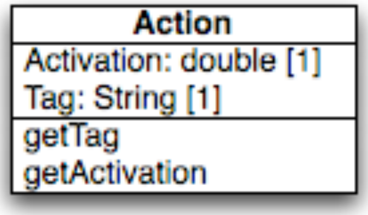


Figure 22 (right): simplified class diagram of the Action class

AlbAgent Farmer motivations: cognitive make-up

A set of stress variables are used to modify the core drivers for each Farmer agent's decision-making. The core (implicit) drivers for decision-making are as follows:

- Achieve an income as great as or exceeding the agent's desired income level
- Maintain debt and debt payments below a desired level
- Maintain perceived levels of social conflict in the locale below the agent's unique preferences
- Maintain water heights in the agent's well according to the agent's preference

These motivations fall under economic, social and hydrologic categories. Associated with each broad category is a single stress variable: Social Stress, Economic Stress and Hydrologic Stress. The stress variables are used as external metrics of agent performance and state of mind, given different ground water banking scenarios. For example: reducing a Farmer agent's income will likely lead to increase economic stress, and may lead to an increased social stress depending on the agent's unique cognitive fingerprint. The agent may respond to this by complaining, or changing its economic strategy. Similarly, pumping water from deeper in the well this year versus last year will likely cause an increase in hydrologic stress, which may also motivate a complaint, or more drastically a switch to secano (lower water use crop). Changes in stress variables are thus indirectly linked to current and future actions.

The Farmer agent also has a number of non-stress variables, which are denoted as internal resources. Internal resources are cognitive variables that only that particular agent has access to and can modify (as opposed to external resources, such as capital, which have substantiation outside of the agent's internal cognition). Examples of internal resources include: fear of government, happiness, confidence, initiative, satisfaction with ground water bank. Example of external resources include: capital, debt, crop choice and harvest volume. GWBSIM's structure of cognitive variables differs in that the BDI separation is much more explicit. GWBSIM agents have '*belief*', '*desire*' and '*resource*' objects aggregating collections of separate variables for the one concept (e.g. a belief about the capital it owns, a desire for a certain level of capital, and an actual real world value for capital). AlbAgent dispenses with this explicit differentiation for reasons of parsimony, but has reworked the concept of a resource. There is no explicit difference between a belief and a resource, and desire is not encapsulated as a preference for the state of an internal and/or external resource (each resource has a set of preference values - minimum, preferred and maximum). AlbAgent does not hard code any resources or variables into the model: they are parameterized via text file at model setup.

While it may seem that the cognitive makeup of GWBSIM and AlbAgent differ in fundamental terms, the essential cognitive model is the same for both: Beliefs supporting Desires that lead to certain Intentions, which generate Actions that may update the agent's Beliefs, Desires and even Intentions. The models mostly differ in the level of sophistication with which the BDI model is implemented. For example, GWBSIM makes use of fuzzy logic and several other forms of translating internal and external variables into an effect on decision making. AlbAgent makes use of simple weighting based on separate or nested IF-THEN rules.

3.2.9 ... AlbAgent agent population

The Farmer agent population is set at 1311, drawn from INE data on land ownership (for agriculturally-active parcels of land). Negative farming population trend projections from INE are used to decrease the population automatically by a certain population each year. In the world, this could be natural population decrease (due to death), emigration from the region, or more likely, changing professions. In the event that a Farmer agent is removed from the model, the farmer's land is distributed equally to the three nearest agents.

3.2.10 ... AlbAgent agent economy

The agricultural economy is simulated at a very coarse scale, making use of both historical data and future projections. Hectares of land with historical crop mixes are assigned to each agent at model startup, and agents then proceed to farm that land according to the assigned crop mix for the remainder of the model runtime, unless they decide to change the crop mix to reduce water use. Production costs and crop prices from 1997 to 2007 are based on historical datasets; costs and prices thereafter (2007 to 2011) are set using annual inflation figures. The array of production costs each agent faces is the same, although quantities are stochastically varied between agents to take account of small variations in the agent's farming practices and operational conditions. Additionally, agents also pay tax and debt, with figures similarly derived from historical datasets and projected according to trend. Harvesting and selling crops represents the principle economic activity of the Farmer agent, but the agent can also make money from participating in the ground water bank (see the specification of the AlbAgent ground water bank, below). No other agro-economic functions are simulated (e.g. land or water purchase or sale).

3.2.11 ... CHJ

The CHJ is an agent with roles corresponding roughly to those of the Confederacion Hidrologica del Jucar. Important roles of the real world CHJ include:

- Administering the water allocation system
- Gathering data associated with the hydrologic system
- Managing the groundwater system through a network of piezometers
- Protecting ecologically sensitive areas
- Flood protection

Only some of these roles are relevant to the simulation. For example, since the simulation of ecologically sensitive areas is not included in AlbAgent, the role of the CHJ in protecting those areas. Roles that are actually simulated include:

- Administration of the water allocation system, with limitations (see discussion below)
- Administration of the ground water banking system (in the GWB scenario)
- Recording and resolution of disputes over water use

Given the focus on parsimony in constructing AlbAgent, many other normal administrative functions of the CHJ are not implemented. For example, the CHJ does not track whether or not an agent uses more of its annual water right than it is entitled to. In addition to the simpler coding benefits this bestows, expert opinions from the region suggest flagrant and unpunished overuse of water in the farming community. So there may be real world support for the assumption that the CHJ does not administer water rights in any rigorous manner. This is in stark contrast to the role of the SME in GWBSIM, which makes a detailed accounting of water use of each canal company for each time step. In realistic terms, the model CHJ agent only performs the following administrative functions:

- Monitoring the overall state of the aquifer and automatically implementing any or all of a number of conservation policy options if the state of the aquifer exceeds certain depletion thresholds
- Receiving, processing and approving/denying applications for ground water banking deposits or withdrawals

If agents perceive inequalities in the distribution of benefits from the ground water bank, or if the ground water bank is leading to unacceptable drawdowns in Farmer wells, conflicts may be generated. These are of three categories of increasing severity: informal complaints, formal complaints and protests. Informal complaints are shared among the immediate neighbors of the Farmer agent, and are essentially a short term means for communicating agent stress. Formal complaints are directed to the CHJ; the CHJ will record but will not act on formal complaints. Protests are directed to the CHJ, which it will record and may eventually act on (such as implementing a water use restriction policy for certain agents).

3.2.12 … CHJ cognition

The CHJ has a vastly simplified cognitive structure relative to the Farmer class. No cognition/action is implemented; instead, a set of event timers with different periodicities repeatedly check whether certain CHJ actions are appropriate at that time. In addition, information received from Farmer agents (unprovoked) can initiate CHJ action. The CHJ has no learning, active memory or emotional components. The CHJ is intended to represent a non-cognitive administrative entity, and so does not have any communication or interaction abilities beyond necessary administrative messages and receiving conflict notifications from Farmer agents.

3.2.13 ... Specification of the AlbAgent ground water bank

The AlbAgent bank is identical in concept to the GWBSIM bank (see earlier discussion), with the following substantive technical differences:

Pricing: the bank has variable pricing depending on the scenario. In scenarios with lower degrees of institutional change (see scenarios discussion below), the market sets the price per unit of water transacted in the bank. In scenarios with higher degrees of institutional change, the CHJ sets the per unit price.

Deposit method: GWBSIM deposits were only possible through direct injection via managed recharge sites. AlbAgent deposits are only possible by foregoing the use of some or all of an existing water right. This system is predicated on the assumption that, without participating in the bank, the agent would use most if not all of its water right. By not using some portion of that right, water exists in the aquifer that otherwise would not have.

Deposit/lease start date: AlbAgent Farmer agents can start leasing and depositing from t = 0 in the simulation, if they so choose. This is not the case in GWBSIM, which calls for an initial delay to allow deposits to build up.

Organization of ground water bank accounts: GWBSIM has a natural feature around which to organize the bank, i.e. hydrogeologically distinct reaches of the Snake River. AlbAgent has no such feature, and the aquifer is not differentiated hydrogeologically within the study area (which is, incidentally, much smaller in geographic area and vertical extent that the Eastern Snake Plain Aquifer. Consequently, an arbitrary cruciform division of the study area aquifer was used, such that there are four bank accounts: north-east (1), south-east (2), south-west (3), north-west (4). The bank account that an agent uses consequently depends on its location.

In all other respects, the rules in the ground water bank are the same for GWBSIM and AlbAgent.

4.0 ... Design Of Experiments: GWBSIM and AlbAgent

The Design of Experiments phase of the work involved the specification of a) the scenarios to be simulated with each model, and b) the concomitant parameterization of each model run. A scenario is defined as a coherent and unique set of model conditions. Parameterization is the process of defining the state of all model variables at the beginning of each model run, in accordance with the specifications of each scenario. In practice, parameterization can be general (some or all variables set to a stochastically-controlled median level) or specific (select variables set up with initial values according to some pre-defined schema. The scenario design approaches for GWBSIM and AlbAgent differed considerably, partly by design and partly by accident. The scenarios for each model were initially considered from the perspective of what kinds of change it would be appropriate to force on each system. In the case of GWBSIM, each simulation would be conducted over a historical time period (1980-2000). This meant that historical climatic and hydrologic data would be used, and so varying climatic as well as institutional conditions would be inappropriate. On the other hand, AlbAgent was part historic, part future in its run (1997-2014). Consequently, in AlbAgent there was more scope for varying climatic as well as institutional parameters, and so more than just institutional scenarios were formulated. Two different parameterization approaches are adopted, on the basis of the different scenario structure for each model.

In GWBSIM, two separate scenarios were simulated, one without ground water banking and one with ground water banking. The Without scenario (referred to as the -GWB scenario) differs from the With (referred to as the +GWB scenario) largely on the options open to individual agents and the responsibilities of the SME. The GWB scenario is based on a detailed specification laid out by Bryce Contor, IWRRI hydrologist, in a March 2007 personal communication.

The original specification of -GWB was as follows:

- **Simulation length**: 20 year simulation length, with daily time steps
- **Agent population**: 1500 SWIs, 1500 GWIs, 80 SUs, 1 PC
- **Hydrological data**: time series (river flow gauge data) from USBR Hydromet, time period 1980-2000.
- **Economic data**: dataset from University of Idaho (1980-2000), annual intervals

The original specification of +GWB was as follows:

- **Simulation length**: 20 year simulation length, with daily time steps
- **Agent population**: 1500 SWIs, 1500 GWIs, 80 SUs, 1 PC, 46 CC, 11451 Aquifer,
- **Hydrological data**: time series (river flow gauge data) from USBR Hydromet, time period 1980-2000, daily intervals.
- **Economic data**: dataset from University of Idaho , time period 1980-2000, annual intervals.

- **Ground water banking** option available to all irrigator and non-irrigator agents (except SME, environment and Market agents)

Adjusted specifications (see discussion in *Results* section) reduced the simulation time period to 5 years, and 10 separate runs under each scenario, but otherwise kept the rest of the specifications the same.

Since GWBSIM is used to test only two scenarios - with and without ground water banking - I deemed it more appropriate to explore variation in select cognitive variables, by applying a Latin Hypercube Simulation (LHS) approach over a population of runs for each scenario. The general intents in running GWBSIM with this parameterization approach were, primarily, exploring the broad conflict outcomes with and without ground water banking, and secondarily, exploring the effects of varying initial agent cognitive states on those same conflict outcomes. AlbAgent was a different model for a different system and with subtly different scenarios. Consequently a different parameterization approach was adopted. All cognitive variables in AlbAgent are established for each agent via normal distributions around median values. Therefore there is no scope for controlled variation. In effect, the parameterization for AlbAgent is by scenario: each scenario in AlbAgent has a distinct set of climatic and institutional variables which are modified according to the scenario's intent. The breakdown of each scenario is listed in Figure 23. Multiple replications with different random number seeds are run for each scenario in order to explore the model's sensitivity to the stochastic components of its parameterization. In the remainder of this section, I lay out the LHS approach adopted for GWBSIM parameterization, and the scenarios/replication approach adopted for AlbAgent parameterization.

Only two scenarios are simulated with GWBSIM. These scenarios are essentially identical in physical and social makeup, except that in the +GWB scenario, the ground water banking institution is available for use by ground water and surface water irrigators. The government (the SME) does not incentivize participation, and so its own institutional activities only vary by having to operate the bank in the +GWB scenario. The internal cognition of individual irrigators does vary slightly, in that ground water banking is made available in their decision making for the plus scenario, whereas in the minus scenario the agents are not aware of the possibility of ground water banking. Note that the agents are not necessarily equipped with any bank-specific cognitive tools; the agents have to adapt to the existence of the banking system with the same cognitive structure they have for the -GWB scenario. As discussed above, given the lack of significant parametric variation between scenarios, I identified a small number of mostly internal cognitive variables to explore via systematic re-parameterization between model runs. The Latin Hypercube Simulation (LHS) approach (McKay et al 1979, Iman and Conover 1980) is a form of sensitivity analysis, which can be defined as the variation of inputs generally by small, incrementally changing amounts in order to determine the effects of individual variables or groups of variables on model outcome (Florian 1992; Pebesma and Heuvelink 1999; Barton 1998; Sanchez 2005). LHS can reduce the number of model realizations required to gain a statistically-significant result, while ensuring that all regions of the parameter space are sampled equally and systematically. In effect, LHS is a form of stratified sampling, the division of a sample space into regular intervals and sampling from those intervals rather than a simple random sample from the entire sample space. In this way, LHS reduces a large multi-dimensional sampling space to a more practical but still statistically credible set of factor levels and combinations (McKay et al 1979, Iman and Helton 1988). The LHS approach adopted was after Florian (1992) and incorporates multiple stages, beginning with qualitative selection of a core set of variables which the modeler believes is critical to the dependent variable in question. This set is then randomly sampled, and the random samples are themselves randomly combined to form the factor set for each simulation run.

LHS was used in GWBSIM in the following steps:

1. A set of factors is identified are were likely to be most critical to the outcomes of the key dependent variables.

   $\{X\} = \langle X_1, X_2, X_3, \ldots, X_K \rangle$
   where K = number of key input variables and $X_1 \ldots X_k$ = the key input variables.

2. An initial realization number (number of parametrically distinct simulation runs, s) is assessed.

   Simulation Runs = s

3. A cumulative distribution function (CDF) using a gaussian distribution is constructed for each factor in the chosen factor set.

   CDF = F_{X_k}

4. Each F_{X_k} is divided into s intervals.

5. Each interval sampled at the centroid.

   I = $F_{X_k}^{-1}\left(\frac{m_{sk} - 0.5}{S}\right)$ where K = 1, 2, 3…k, m_{sk} is the rank number of the s^th^ simulation for input variable X_k, and $F_{X_k}^{-1}$ is the inverse CDF.

6. An s x k (Figure X) matrix is constructed by randomly sampling once from the interval sample (I) selection for each variable.

7. The s x k is used to parameterize each of s runs.

Figure X: Latin Hypercube Simulation setup (after Florian 1992)

Parameter	1	2	3	4	5	6	7	8	9	10

Social capital	0.00898098010145651	0.295736252118898	0.991646953769207	0.662737806068191	0.875736406810724	0.70894952196906	0.567516048212759	0.429471284222054	0.102954146354417	0.341415885269794
Conflict levels	0.671835912258192	0.572525080472868	0.256052185195512	0.380752405120628	0.0690233108962655	0.78524797316162	0.924458442056559	0.467198718898987	0.193882020813797	0.849159259649586
Future mitigation	0.300764044303301	0.292245331021916	0.758456855240098	0.687200003897745	0.00156127628912156	0.969460277739233	0.494203493932268	0.518652535537603	0.814454840233551	0.122002143656205
Happiness	4.77175959264185	6.37786172036713	2.41131067191114	3.65669298364619	9.77186384379514	5.07493406790555	8.92273646026202	1.91800944611885	0.548507925282932	7.11017813576894
Initiative	5.08989299674261	1.20779812692222	4.18253168722904	3.93189338898145	2.28138565543473	6.17509110591593	7.45754748114375	9.28782675254185	8.42453290909667	0.239636778503348
Curiosity	3.19530566351213	8.56559628867384	9.57112357155727	2.95996886025694	4.60579831872831	1.54228386881574	6.14324401853403	5.88940813185678	0.807499249620314	7.06983826040252
Hostility	9.81682020644883	2.90228429214512	6.30075069781281	7.26237817545025	8.50387208604272	4.12654461139673	0.367137294312746	1.80809678978111	5.59064094426064	3.93187935499591
Suspicion	9.72591918936921	8.34634451358034	6.65805119940942	4.56127113606125	5.88221624645039	7.78979960075041	1.77069884254655	3.74255145843777	2.49293606789847	0.762525566656414
Capital	465906.381772499	785794.098649096	1042080.49270272	350695.532879345	1743216.0023674	1501130.90044325	1216073.21426612	161266.005285582	828328.938297323	1960585.68317653
Debt	30811.9041658727	39500.6973399214	23483.4859526513	45654.9901599598	11529.7003708491	10579.9185808843	3983.24011393585	41065.9945617608	29634.6685334982	17449.0860917579
Interest	0.663492117922113	0.937775428079543	0.152109183673794	0.353557855145751	0.837845654708006	0.546627049178032	0.455845917835176	0.738122712061434	0.218798108446227	0.0330198036539189
Income stress	0.180875414739191	0.994981757161547	0.385641878192524	0.603026307251826	0.720088213516517	0.860252108985837	0.221873595833285	0.0485478009371593	0.563220036435277	0.43868478497255
Water stress	0.140170633312552	0.338560835528949	0.203447469862157	0.872828241213623	0.782232263074392	0.0146291450224651	0.561104730516417	0.607429557095488	0.940374495504882	0.417153663425959
Model trust	0.410015411984869	0.314613208241664	0.0166044022574218	0.9232593752791	0.744102064904 56	0.206468241154822	0.528789736840905	0.199303008771674	0.687532262569473	0.843040772109037

Figure X: actual table of parameterization values used in both scenarios in GWBSIM. Note that 'Conflict levels' refers to the variable defining the agent's perception of the current level of conflict in the basin. 'Future mitigation' refers to the variable defining the agent's belief in the likelihood of some form of mitigation being forced onto GWI agents in the future.

AlbAgent enjoys a wider range of scenarios and so much richer possibilities for varying non-cognitive parameters. Consequently, a scenario-controlled parameterization was adopted in favor of an LHS approach. The parameterization was established from the qualitative premise that two areas of change are of particular significance for the Albacete region from the perspective of conflict: climate and institutions. These provided two axes to map out all possible scenarios. An LHS approach would also have been appropriate here, since the number of possible combinations of parameters and parameter values leads to a combinatorial explosion. Even with an LHS approach it was clear that the number of model runs required to adequately explore the sample space would be well beyond the time and resources available. Consequently, an alternative, more parsimonious approach was adopted: dividing the sample space of climatic versus institutional change into 9 separate and qualitatively-defined scenarios. In this way the low, moderate and high states of change for both climate and institutions can be explored in combinations that test the extremes (no climatic and institutional change versus maximum climatic and institutional change, etc) and the median states (some climatic and institutional change). While this does not fully explore all the possible dynamics between climatic and institutional change and any links with conflict, it does allow us to put bounds on the major hypothesis and at the very least suggest a direction for future exploration. Figures 23 and 24 below describe each scenario in detail.

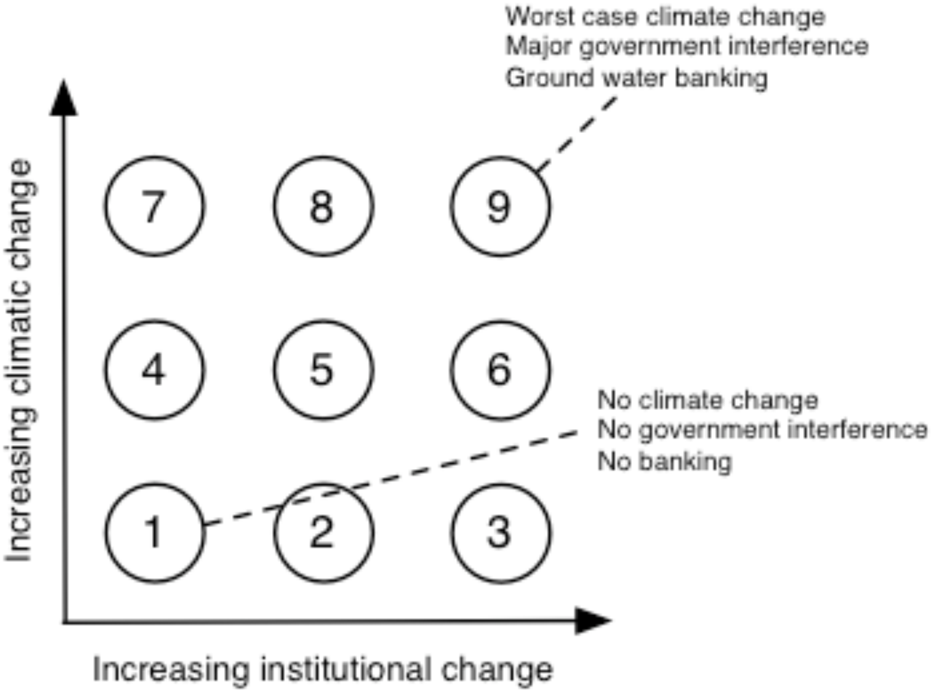
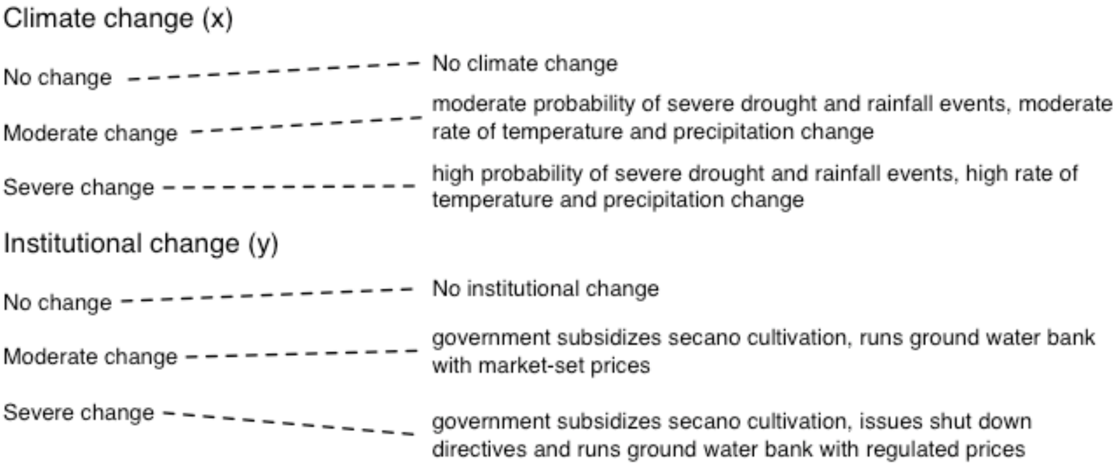


Figure 23 (right): numbered scenarios, qualitatively classified on axes of increasing climatic and institutional change. 'Worst case climate change' corresponds with the upper limits of the IPCC's projections for precipitation and temperature changes; 'major government interference' means that the government (CHJ agent) is allowed to intervene in the system through selective subsidies and direct pumping shut down orders, and will intervene with high probability; 'no banking' means that the ground water banking institution is neither available to agents nor are they aware of the possibility of banking.

Scenario Number	Extent of climatic change	Extent of institutional change
1	Low	Low

Scenario Number	Extent of climatic change	Extent of institutional change
2	Low	Moderate
3	Low	High
4	Moderate	Low
5	Moderate	Moderate
6	Moderate	High
7	High	Low
8	High	Moderate
9	High	High

Figure 24: tabular form of Figure 23 above, indicating the qualitative dimension of climatic/institutional change associated with each AlbAgent scenario. Dimensions are explained in more detail in Figure 25 below.



Climate change (x)

No change	No climate change
Moderate change	moderate probability of severe drought and rainfall events, moderate rate of temperature and precipitation change
Severe change	high probability of severe drought and rainfall events, high rate of temperature and precipitation change

Institutional change (y)

No change	No institutional change
Moderate change	government subsidizes secano cultivation, runs ground water bank with market-set prices
Severe change	government subsidizes secano cultivation, issues shut down directives and runs ground water bank with regulated prices

Figure 25: detailed explanation of 'low', 'moderate' and 'high' change dimensions for AlbAgent scenarios

4.1 ... Methodological Limitations

A number of problems emerged during the course of preliminary GWBSIM runs that were deemed likely to damage the quantity and quality of output data from the final set of runs. It was soon clear that rectifying these problems would require major reconstruction of the core cognitive and environmental engines of GWBSIM. Unfortunately, there was not enough time to complete these changes before moving onto AlbAgent development. Consequently, I partly modified the experimental design to account for these changes, which has limited the analytical scope accordingly. Some of the problems and methodological limitations with GWBSIM are discussed in more detail in the results, but are listed here as a summary:

1. *Corruption of environmental output databases*: analysis of the relationship between river flows, river diversions and measures of system conflict was not possible.
2. *Shortened simulation time period*: only 5 years out of the full 20 years were simulated.
3. *Limited tracking of outputs*: only a few key variables, selected a priori as important, were recorded. This meant that the analysis is restricted to these variables and other possible causative relationships may go unexplored.

One of the most critical limitations for GWBSIM is the lack of environmental results data (river flows and diversions), since water is the most central and essential resource driving the system. Due to the lack of this data, I do not attempt to draw any major conclusions relating environmental conditions and agent behavior. However, to frame that discussion I briefly explore here trends in the historical data used to parameterize the model. River flows were set up using Bureau of Reclamation HYDROMET data for 13 gauging stations up and down the Snake. Note that these are highly simplified inputs, since many other layers of input (ground water bank activity, diversions from the river and return flows back into the river) were not simulated. What this brief analysis will be able to show us is whether the 5 years of simulation achieved (out of a possible 20) were particularly unique hydrologically. Figure 26 shows some basic probabilities for this hydrologic dataset:

Probability of a gauging station having its...
...**highest** flow **after** 1985: 0.53
...**lowest** flow **after** 1985: 0.46
...**highest** flow **before** 1985: 0.46
...**lowest** flow **before** 1985: 0.53

Figure 26: basic probabilities for gauging station flow, 1980-2000

This cursory analysis shows that most gauging stations have a significantly higher probability of seeing their highest and lowest flows in any given year before 1985, suggesting that hydrologic variability was high for this initial few years. Per-year means calculated for all gauging stations (Figure 27) suggest that the first 5 years of the simulation were either at or above the 20 year average; the middle 10 years were at or below average, and the last 5 years were consistently above average.

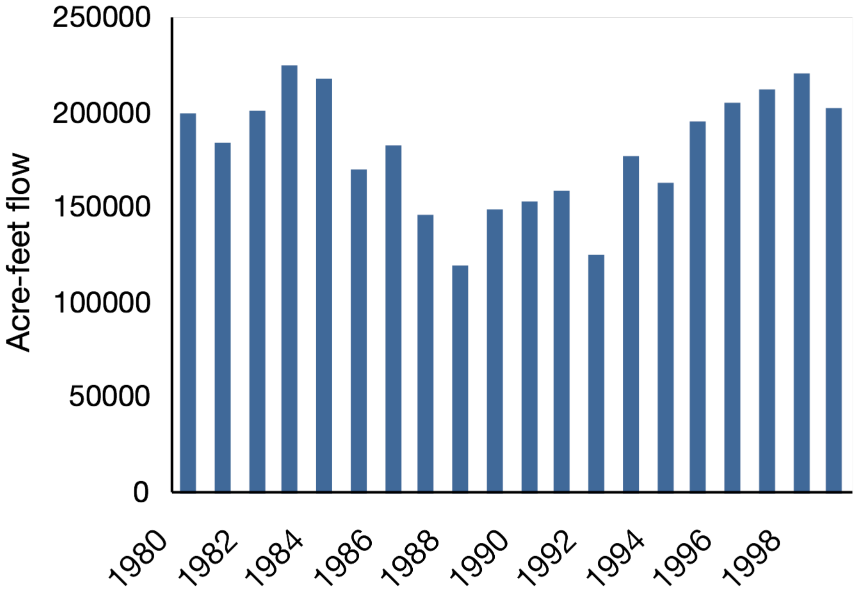


Figure 27: average flow per year across all gauging stations. The red line marks the approximate position of the 20 year average.

Implications for analysis are as follows:

- The first 5 years of the simulation most likely had much higher base hydrologic variability than later years.
- The first 5 years did not contain the driest year, but did contain the wettest year.

At this point, however, I must re-emphasize the limitations of this approach: these flows are the basis for later decisions by agents. These decisions are very likely to substantially alter the base flows in the Snake, either through participation in the ground water bank, diversion of water from the river into canals, evaporative loss through crop growth, or return flows back into the river. This pre-simulation work provides a general environmental 'frame' for the analysis, but because of the potential difference between the base flows in parameterization and the actual per-year flows of the simulation, are not used in any substantial way in drawing conclusions or suggesting causation.

The methodological limitations for AlbAgent did not arise from problematic code, but more from data scarcity. This mainly influenced climatic, hydrologic and economic components of the model. Data was rarely absent, but typically only available at very coarse scales: some economic data was only available for the whole of Spain, for example, and so needed to be qualitatively scaled and adjusted for the Albacete region.

This was particularly true for the hydrology, with very coarse aquifer recharge and discharge data leading to a highly simplified bathtub model of the aquifer versus a more desirable finite element approach. Most importantly, there were significant gaps in the record of conflict for the region over the past 10 years. Different expert sources suggested different forms as well as degrees of conflict within and between communities, and there were no easily accessible records of litigations, official complaints or other reasonable measures of conflict. Consequently, full calibration was not possible, and AlbAgent remains a model with exploratory rather than predictive power. This is something I must emphasize for both models: neither is intended as an accurate and precise representation of their respective systems. Each model is constructed with as much real world data as it was practicable to access in the time available; in most cases, however, this was not sufficient, and so considerable license has been taken in filling in the gaps. Consequently, both models are intended to explore theory and not to offer concrete predictive recommendations for either setting.

5.0 ... Results

5.1 ... Final experimental specifications

5.1.1 ... GWBSIM

In the final results run, I conducted 50 replications (fixed seed) for each of 2 scenarios (100 total runs), +GWB, and -GWB. I used a Latin Hypercube parameterization to vary select cognitive variables between replications, and the same LHS parameterization set for each scenario.

5.1.2 ... AlbAgent

I conducted 100 replications with random seeds for each of 9 scenarios (900 total runs). Scenarios varied climatic and institutional variables according to a predefined table. The greater number of replications run for AlbAgent reflected in part avoidance of the problems encountered in GWBSIM, and in part from the simpler and more efficient code in AlbAgent.

5.2 ... Presentation and analysis of results

I explore the results in three thematic groupings: GWBSIM results, AlbAgent results, and a comparative analysis. Both GWBSIM and AlbAgent results are discussed in isolation, since the Albacete and Idaho systems are fully independent and the models are able to stand on their own as fully self-contained representations of the systems. The comparative analysis draws on select results from both models that provide a comparative overview relating conflict to institutional capacity in each setting. Note that standard deviations are not included in the graphics unless they were significant enough to warrant discussion in the text.

For each model, I explore the results under further broad headings: conflict dynamics, ground water bank performance and possible causative relations between internal agent variables and conflict levels in the system. Each section includes a short summary after the analysis to aid the reader. The section begins below with a brief refresher of the original hypothesis, which guides the initial selection of results for analysis.

5.2.1 ... GWBSIM

I stated the major hypothesis as follows:

Major Hypothesis:

“Any change to institutional capacity will have an effect on the dynamics of water conflict in an artificial social-hydrological system”

Conflict frequency (number of court actions and complaints) and conflict severity (number of distinct agents filing court actions or generating complaints) are the most critical output variables in helping us to explore the major hypothesis. Court action frequency and severity represents a more significant expression of conflict than a complaint, since the court action requires more energy, initiative, expense and cooperation on the part of the plaintiff agents than simply generating and posting a complaint with the SME. The following plots show conflict frequency and severity for each year of each scenario. Note that in these, as in all other GWBSIM plots, data is aggregated to an annual level. This was in fact the only available data resolution that the modeling platform made available at the time of experimentation. An update to the platform (AnyLogic) later made available a class of statistical variables that provided more detailed resolution of data, which is why the AlbAgent data is provided on a per-time-step basis.

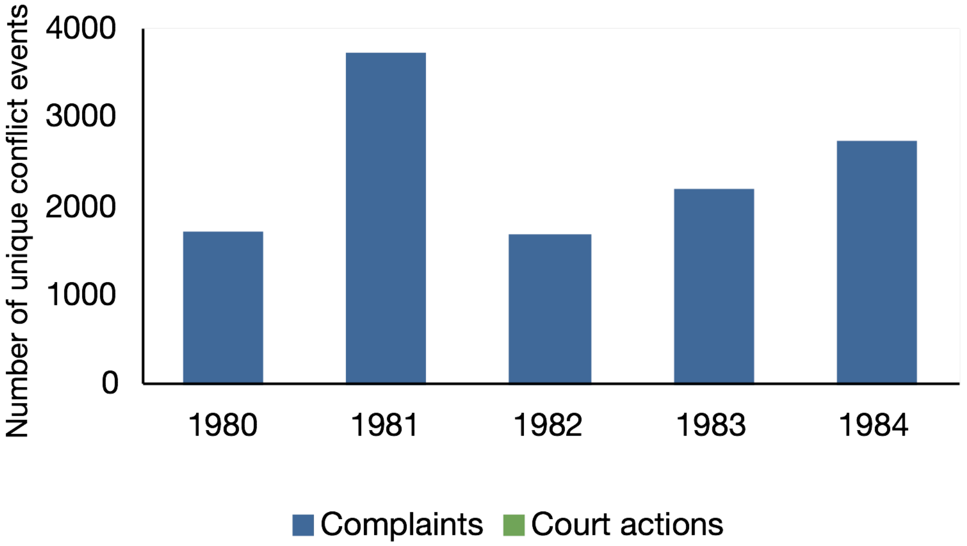


Figure 28: complaints and court action frequency in the +GWB scenario

In Figure 28, note that a single event is either a single complaint filed with the SME, or a single court action launched by one agent or group of agents against another agent or group of agents. The first important detail to note is that no court actions were encountered in any runs in the +GWB experiment. A significant number of complaints were encountered, however. Figure 29 below adds in the data from -GWB, indicating that the scenario without ground water banking overall had a higher conflict frequency, although in 1981 the +GWB scenario exceeded the -GWB scenario in absolute conflict frequency.

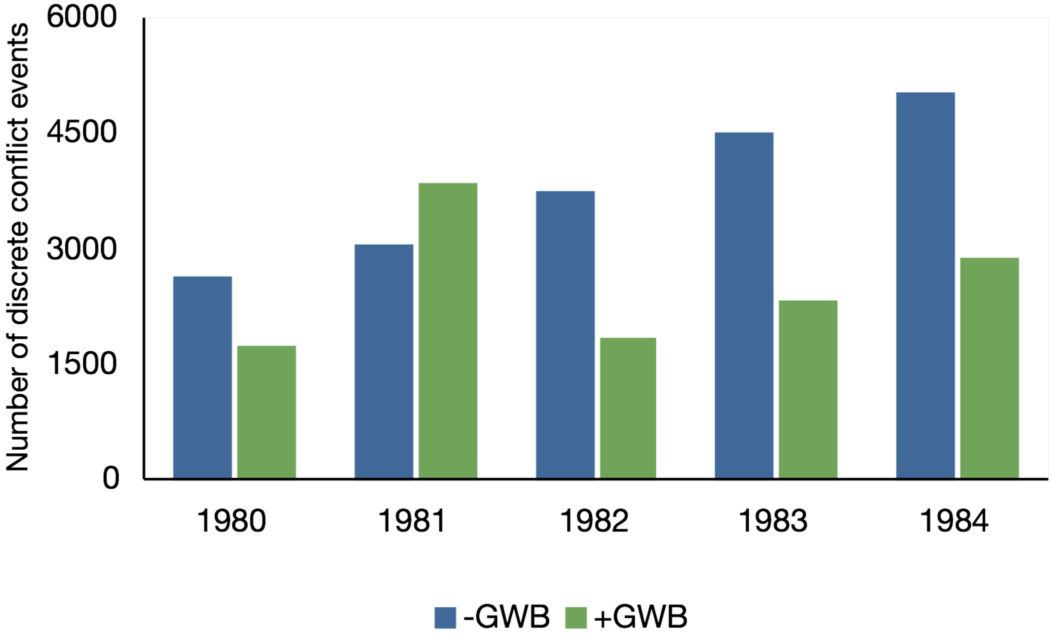


Figure 29: conflict frequency in an inter-scenario comparison.

Looking in more detail at -GWB, Figure 30 below displays the total complaints per year (averaged across all runs in the experiment). Complaints peak around 1983, and then start to decrease. Note that this does not necessarily indicate a trend, since the model was designed to run for 20 years in simulation time, not 5.

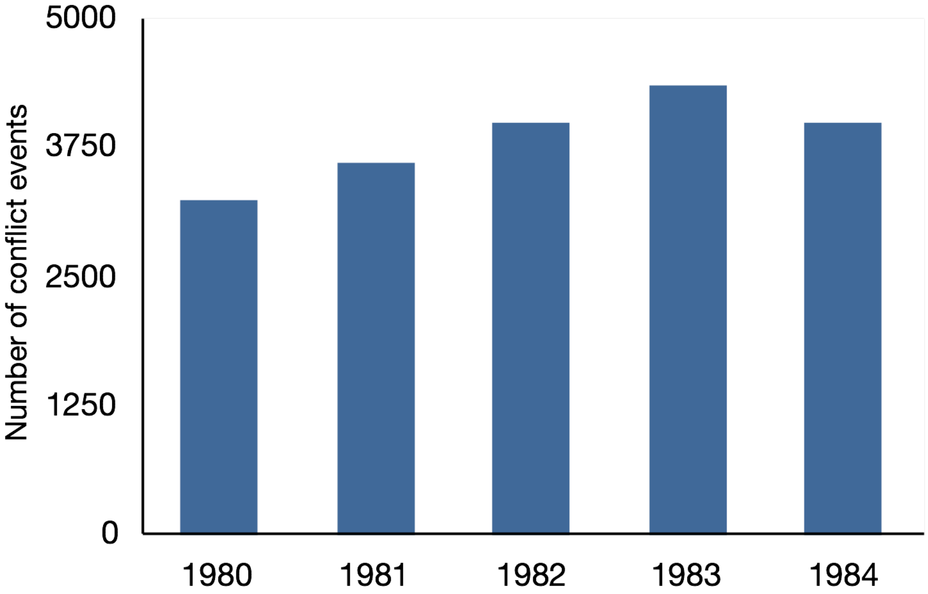


Figure 30: total complaints each year of the -GWB scenario, averaged across all runs.

Figure 31 below shows the court action data for the -GWB scenario. Court actions also peak later in the simulation, in 1984, and have a low in the second year of the simulation.

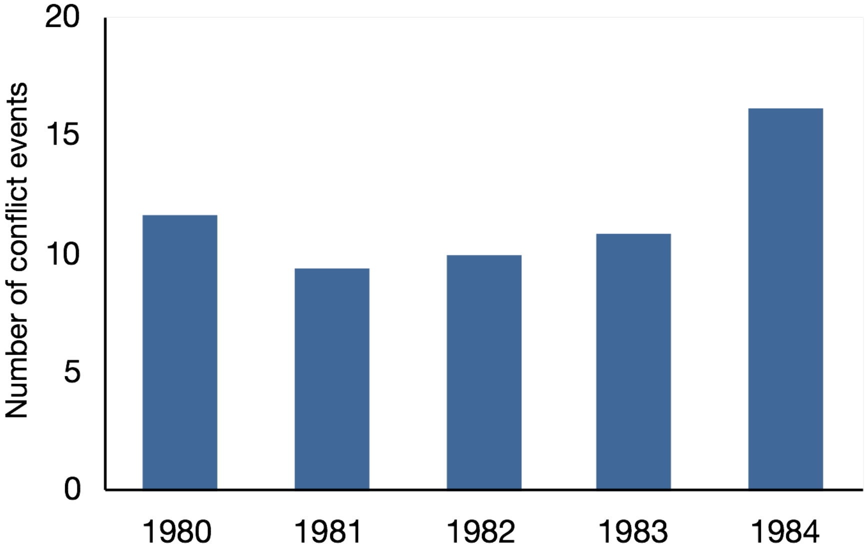


Figure 31: total court actions for each year of the -GWB scenario, averaged across all runs.

Figure 32 below compares the complaints of both scenarios, showing that while overall the -GWB scenario had a higher complaint (and conflict frequency), the +GWB scenario did exceed -GWB in absolute number of complaints in one year: 1981.

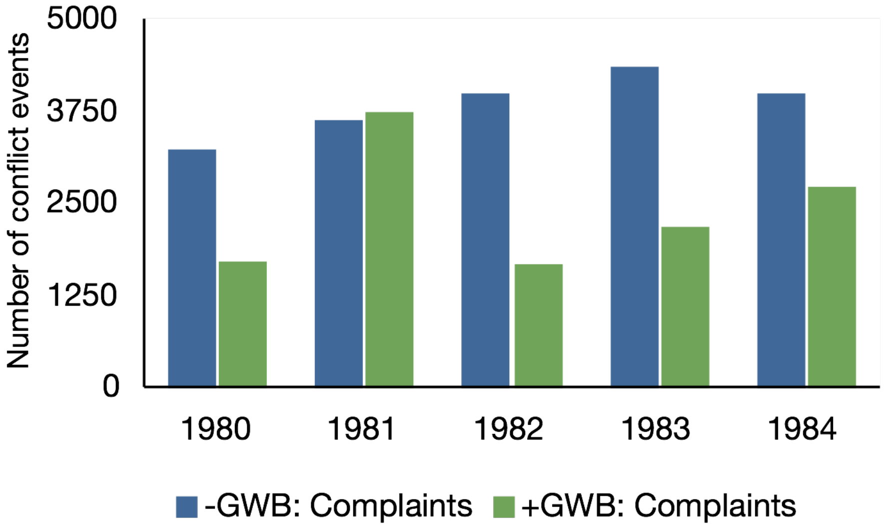


Figure 32: complaint frequency compared between scenarios, averaged across years.

There was a significant difference between the two scenarios in terms of conflict frequency: no court actions were encountered in +GWB at all, whereas at least 5 court actions a year were encountered for all years of the -GWB scenario.

Figure 33 shows the conflict severity for each scenario. 100% conflict severity corresponds to all agents of all types filing a court action and/or complaint at the same time. For the +GWB scenario, no court actions were generated, and so conflict severity is only shown using complaint data: in other words, 100% severity would equate to all 4662 active cognitive agents complaining at the same time. Note that a single court action 'unit' equates to an agent either instigating or participating in a court action. As discussed earlier, agents are able to cooperate over the generation of court actions, but there can only ever be a single agent instigating an action.

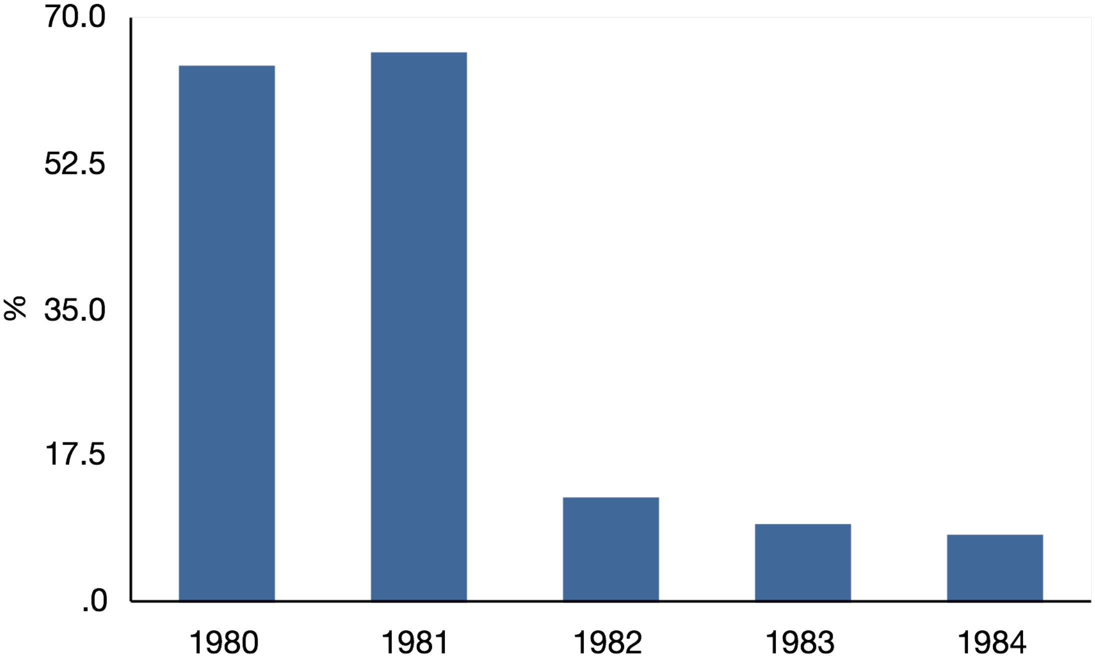


Figure 33: conflict severity as % of maximum for the +GWB scenario.

Figure 34 below shows conflict severity for -GWB, indicating that at no point was the scenario ever severely under conflict with regard to court actions. The maximum percentage of agents participating in a court action never exceeded 2.5% of the total. However, the presence of court actions altogether - a much more costly activity for agents - suggests that the overall conflict severity for -GWB was higher than +GWB.

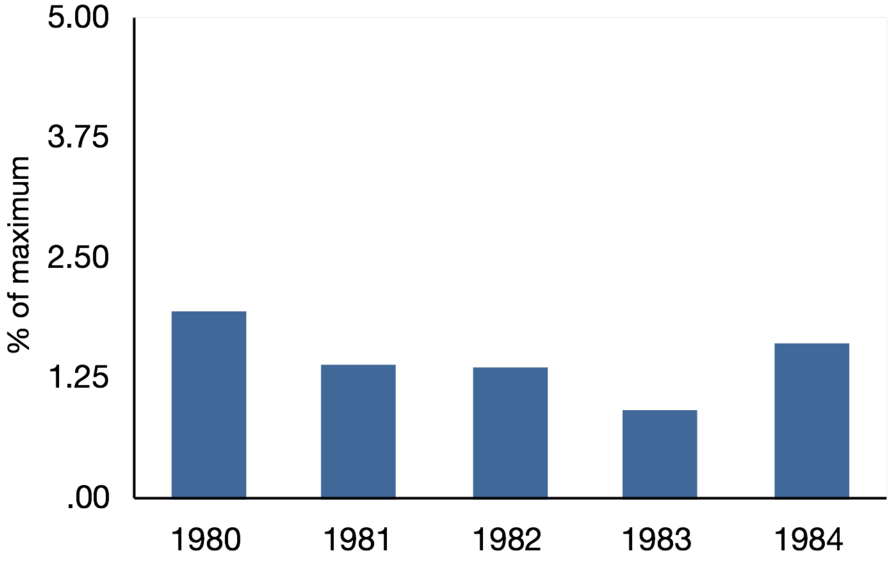


Figure 34: conflict severity as % of maximum for the -GWB scenario.

Figure 35 below shows a comparison between the two scenarios for conflict severity - calculated for complaints, since the +GWB scenario had no court actions. The graph indicates that while conflict severity (complaints) was similar for both scenarios initially, conflict severity decreased significantly thereafter for +GWB but kept rising for -GWB.

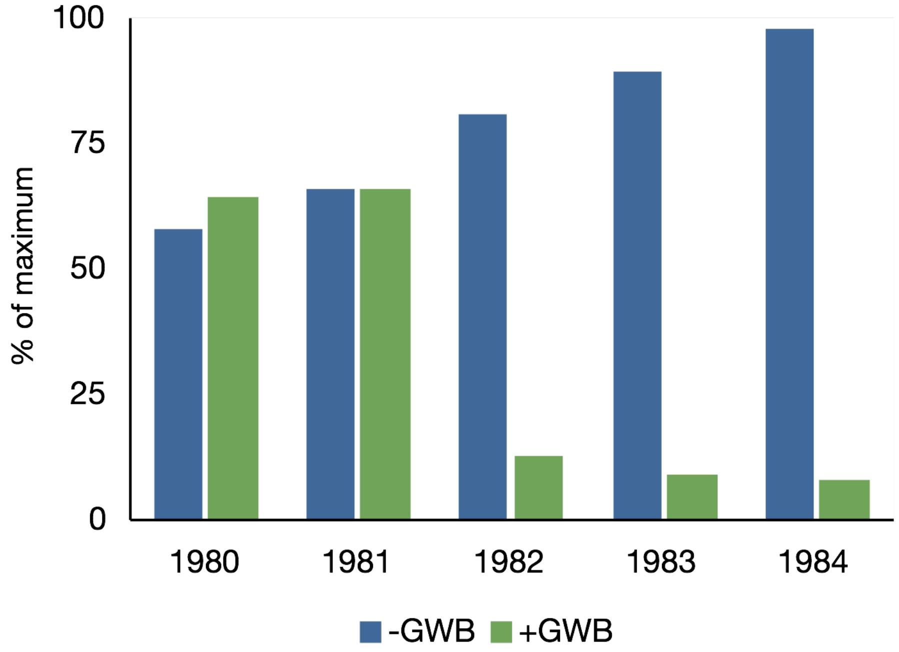


Figure 35: comparing conflict severity between scenarios.

5.2.1.1 ... Results Summary 1-A: conflict in the basin

In summary, then, the complaint and court action data from the two experiments shows that:

1. The -GWB scenario showed overall higher levels of conflict frequency and severity across all years of the simulation, in terms of both complaints and court actions.
2. The level of court action-related conflict severity was low for -GWB, but still significantly higher than for the +GWB scenario.
3. The +GWB scenario showed low levels of conflict frequency and severity in general, with no court actions encountered at all in any year.
4. The +GWB scenario matched the -GWB in terms of complaints for the first couple of years of the simulation, but thereafter showed a significant decrease in conflict severity and frequency. The -GWB scenario showed a steady increase in complaint frequency and severity over time, but a relatively stable level of court action frequency and severity over time.

I designed the +GWB and -GWB scenarios primarily to help explore what happens to the degree of water conflict in an artificial society with and without a ground water banking system. At face value, a lower level of conflict in the artificial society for the +GWB scenario would imply success for the ground water bank in reducing conflict. However, it is important to gauge what the intensity and form of participation in the bank before suggesting it could have had a significant effect on any trend seen in conflict. In other words, I must begin to construct a case that the ground water bank was principally responsible for the marked differences in conflict levels that the results for GWBSIM have shown so far.

Figure 36 below shows that GWI agents were the only participants in the bank for both withdrawals and leases, and that these numbers were significant - on occasion approaching and even exceeding one deposit/lease per agent per year.

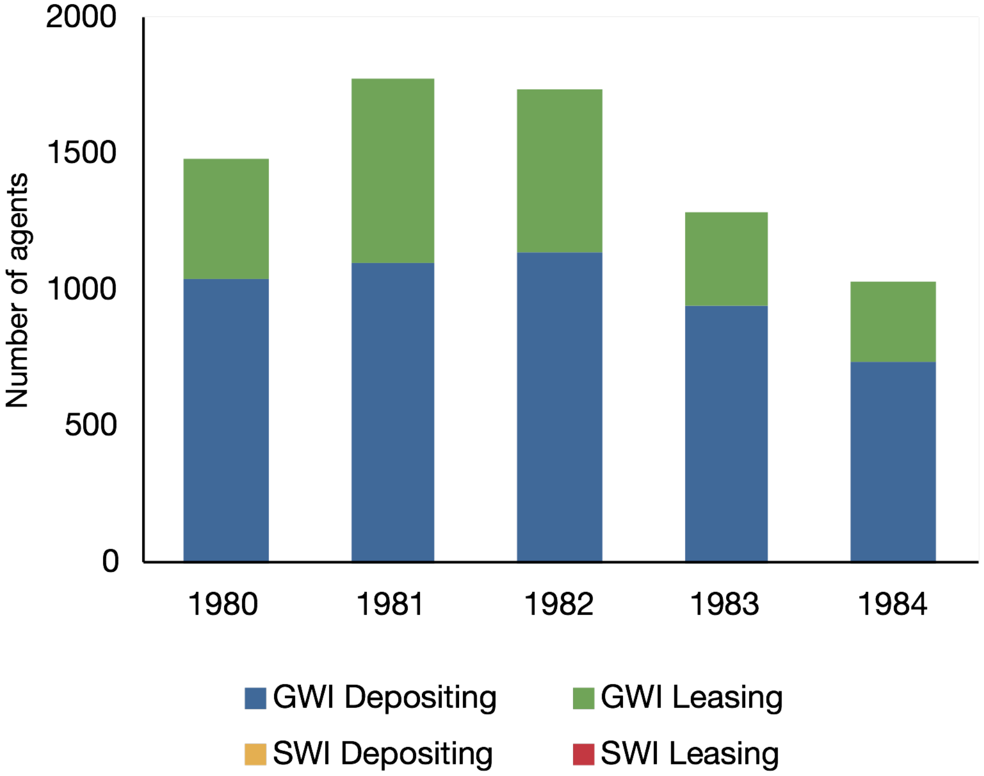


Figure 36: participation in the ground water bank, by agent type and year, +GWB scenario

This suggestion is reinforced by Figure 37 below, where participation in the bank peaked at around 25% of the total GWB-active agent population. Note that only GWI and SWI agents were permitted by the rules of the bank to participate. This was in part practical (limiting the complexity of the bank and the simulation) and in part realistic, since these are the two irrigator types most likely to participate in any real ground water bank in the Eastern Snake (and indeed, most likely to have a motivation for participating: Contor, pers. comm. 2007).

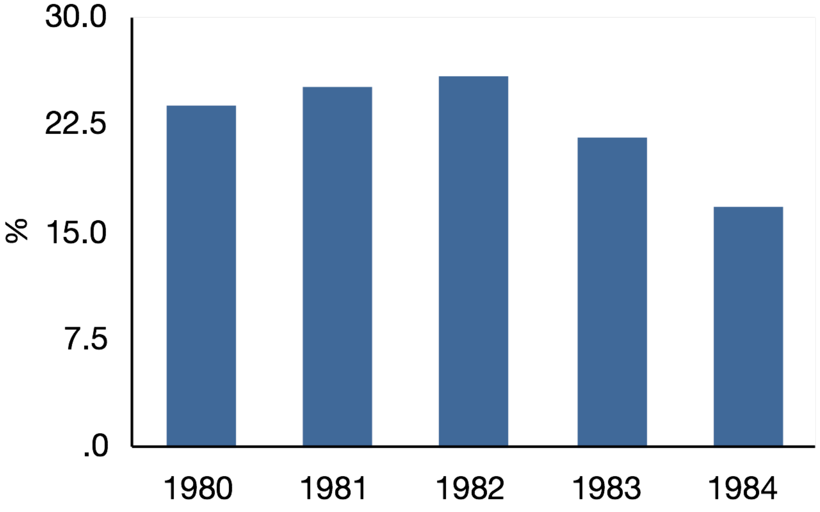


Figure 37: participation in the bank as a % of potential maximum, across all years of the +GWB scenario.

Importantly, Figure 37 shows an initial steady increase in participation followed by a steady decrease towards the end of the simulation.

Figure 38 below shows that total volumes leased and deposited from the bank were healthy, although deposits greatly exceeded leases. Deposit volume per participating agent actually increased over time, if we take into account the steady decrease in participation observed in Figure 37 above. Total transaction volumes peaked at around 1.5 million acre-feet in 1982. The pattern of leases over time shows an intriguing pattern of sharp increases towards the middle of the simulation run followed by sharp decreases back to nearly 0 leases by 1984.

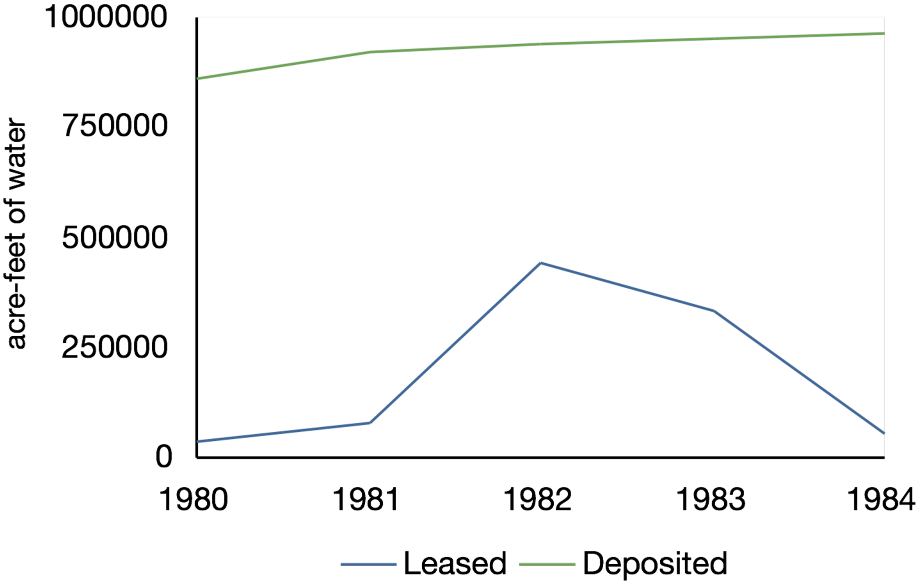


Figure 38: volumes deposited into and leased from the bank.

Figure 39 below shows the volume of water in the bank responding to the dominance of deposits over withdrawals, with the bank nearly 4 million acre-feet in credit by the end of the simulation. This is a substantial quantity compared with the annual flow of the Snake River (typically between 8 and 12 million acre-feet annually). Between 1983 and 1984, for example, around 800,000 acre-feet were added to the aquifer (and, eventually, to the river by virtue of hydraulic connectivity in the system), around 10% of the river's annual flow.

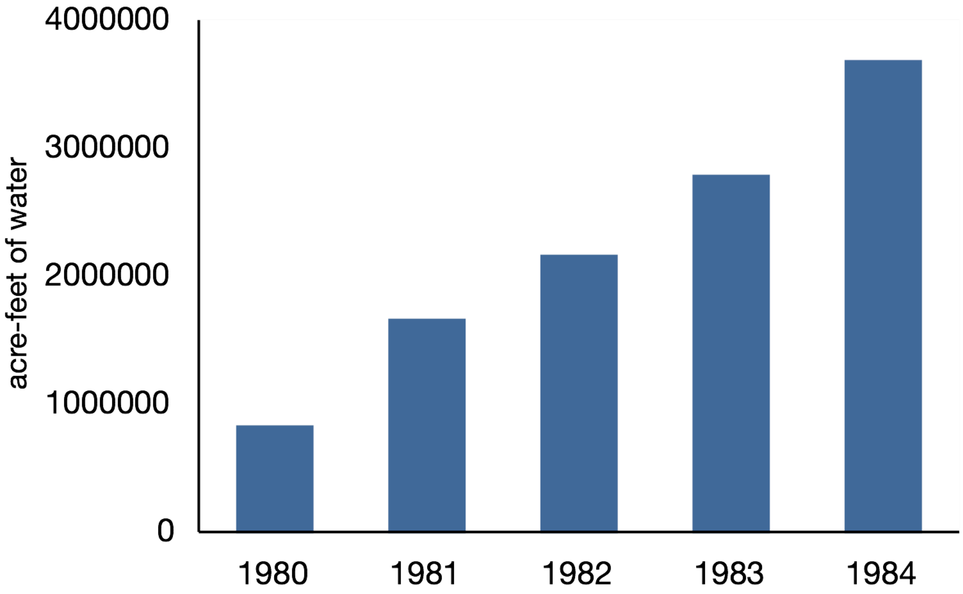


Figure 39: total volumes of water in the bank over time.

5.2.1.2 ... Results Summary 1-B: performance of the ground water bank

In summary, this brief examination of the state and performance of the ground water bank has shown that:

1. GWI agents dominated both leases and withdrawals from the bank. Note that only GWI and SWI agents were allowed to participate in the bank.
2. GWI deposits were a far more significant contribution to the bank than leases. This was reflected in the overall upward trend in the bank's balance over time.
3. Deposits increased in volume over time, and the per-agent deposit volume also increased. Leases showed no such trend, peaking in mid-simulation but decreasing to near zero by the end.

The above graphics have attempted to convey the evolution of each scenario over time using the principal metrics of conflict frequency and severity (proxies for the hypothesis-defined concept of conflict dynamics), as well as details regarding the transactions into and out of the ground water bank. It is clear that the bank was reasonably successful and that the banking scenario saw less conflict than the non-banking scenario. This having been made clear, I will now move onto exploring possible correlations between the various characteristics of each agent type and the overall conflict frequency and severity in the model. While a correlation is never absolute proof of causality, it does provide substantial food for thought and can help contribute to or detract from the central hypothesis. First, through correlations and multiple regressions, I explore the relations between the parameterizations of key variables conducted as part of the Latin Hypercube Sampling. In other words, I am posing the question: does the initial parameterization for the pre-selected key variables have a statistically significant effect on the year-by-year level of conflict in the artificial society? Second, through covariance analyses, I explore possible correlations between changes in agent characteristics over time, and conflict frequency.

Figure 40 below shows correlation values for all parameterizations compared with number of complaints (+GWB scenario, where no court actions were encountered). This is a plot of initial parameterization values against a major model outcome, the number of complaints per year, not variation in those parameterizations over simulation time. Note: ‘Conflict levels’ denotes the agent’s perception of conflict levels in the basin; ‘Future mitigation’ denotes the agent’s assessment of the likelihood of future mitigation requirements being handed down from the SME. A mitigation requirement is essentially a penalty dealt out to agents who are ruled by the SME to be in breach of the prior appropriation doctrine (i.e. causing some damage to senior water rights upstream or downstream). Mitigation plans are usually settled out of court, through diverting some of that agent’s water right to the injured party, and other ‘mitigating’ actions. All active cognitive agents in the model were imbued by its parameterization with a varying level of suspicion as to the likelihood of these mitigation plans being forced upon them or other agents during the simulation or at some point in the future.

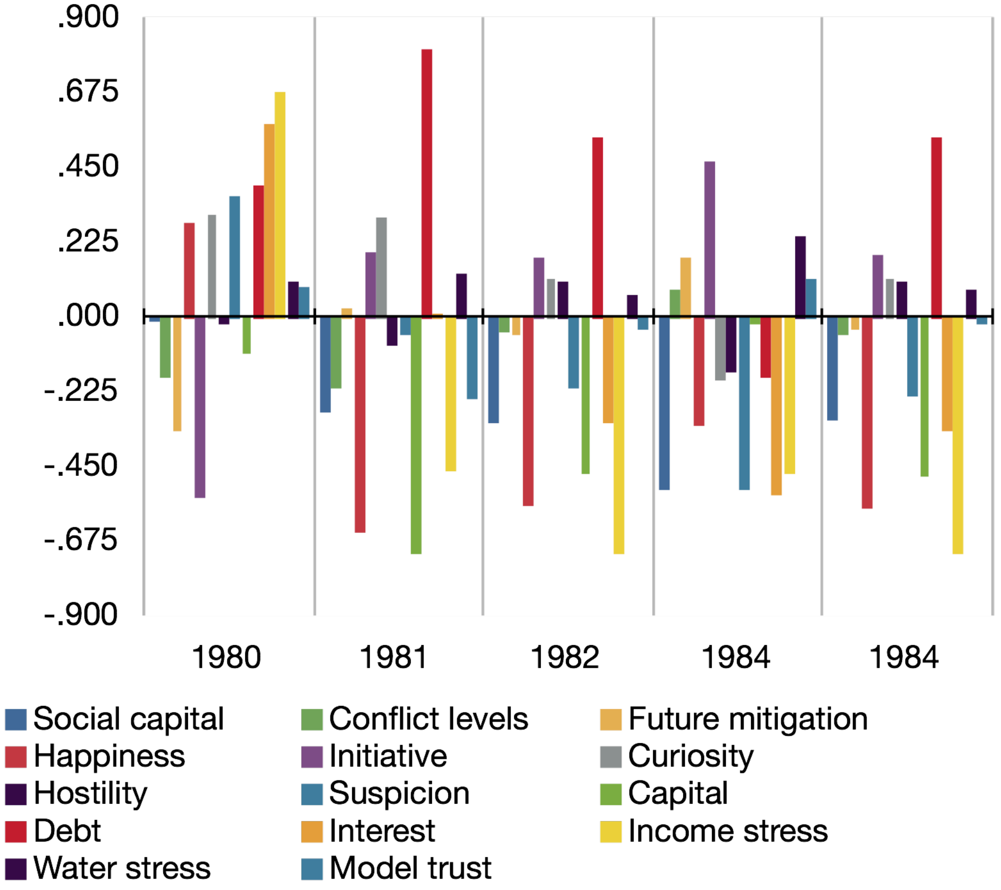


Figure 40: correlation coefficients for comparisons between LHS-parameterized values and the resultant number of complaints per year for the +GWB scenario.

Some of the most evident features are: the strong positive correlation between debt and complaint frequency; mostly negative correlation between income stress and complaint frequency; and mostly negative correlation between capital and complaint frequency. The signs of these correlations are mixed: in most years, a higher debt is related to increased numbers of complaints, with reasonable significance. However, income stress is related to both increases and decreases in complaints. This suggests confounding variables may be reducing the significance of that relationship over time. The increase in capital is generally inversely correlated with complaint frequency, meaning (in a not unsurprising finding) that an increase in an individual agent's capital is likely to result in a lower complaint frequency from that agent.

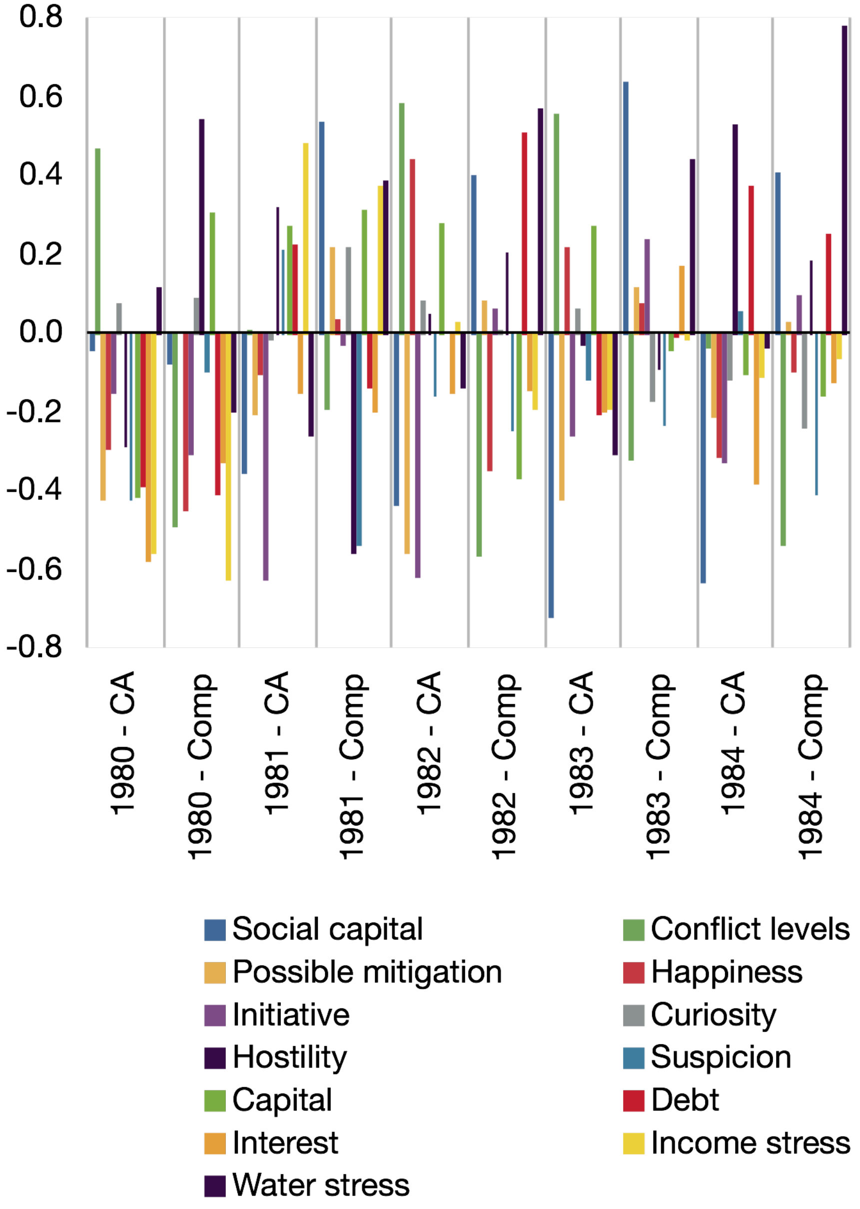


Figure 41: correlations for the -GWB scenario, comparing LHS-parameterized agent characteristics with result complaints and court actions in each year of the -GWB scenario.

The same plot for the -GWB scenario is more complex because both complaints and court actions are included as dependent variables. Some notably significant relationships appear to be:

i. Water stress and complaint frequency, very strongly and positively correlated.
ii. Social capital and complaint frequency, strongly correlated both positively and negatively.
iii. Initiative and court actions, moderately and negatively correlated.
iv. Perception of conflict levels and court actions, moderately positively correlated.

v. Moderate negative correlation between suspicion and both court actions and complaints.
vi. Consistent weakly negative correlation between debt and complaints/court actions.

Other relationships are present, but these are at best weakly correlated or contradictory between years. Only water stress has a correlation coefficient large enough to stand out.

In Figures 42 and 43 below, we conduct a simple (normalized) covariance analysis for variation in agent characteristics over time against complaint frequency for GWI and SU agents, +GWB scenario. Some of the most notable features are as follows:

i. Strong negative covariance between capital and complaint frequency.
ii. Moderately strong positive covariance between social capital and complaint frequency.
iii. Moderately strong negative covariance between a variety of mostly ‘negative’ emotional variables - hostility, suspicion and perception of future mitigation - and complaint frequency. ‘Negative’ in this context is a somewhat subjective label, but attempts to convey the assumption that ‘hostility’ is generally agreed to be an emotion with unproductive consequences for human society. This is an interesting relationship, given that one might expect such ‘negative’ emotions to lead to behaviors that were more aggressive and hostile - such as complaints. However, this does not appear to be the case.
iv. A lack of a clear covariance between income stress, water stress and complaint frequency.

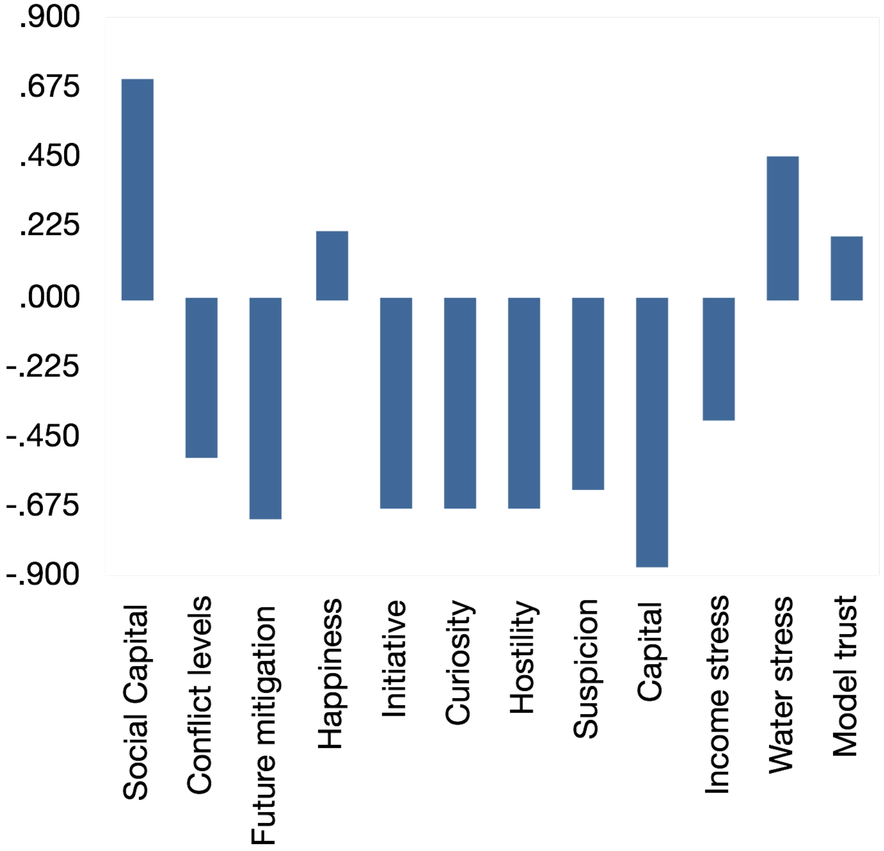


Figure 42: covariance between agent characteristics and complaint frequency over time for the +GWB scenario. Note that the variance has been normalized to plot on a 0.0-1.0 scale.

Figure 43 below shows the same normalized covariance for the SU agent. A very different picture emerges: whereas most emotions for the GWI agent appear to be inversely related to complaint frequency, for the SU the opposite is true. Higher hostility, curiosity, initiative and suspicion all are apparently related to higher complaint frequency from the agent. Social capital and financial capital are once again strongly positively and negatively (respectively) related to complaint frequency, and this time income stress and water stress have a much stronger and positive relationship.

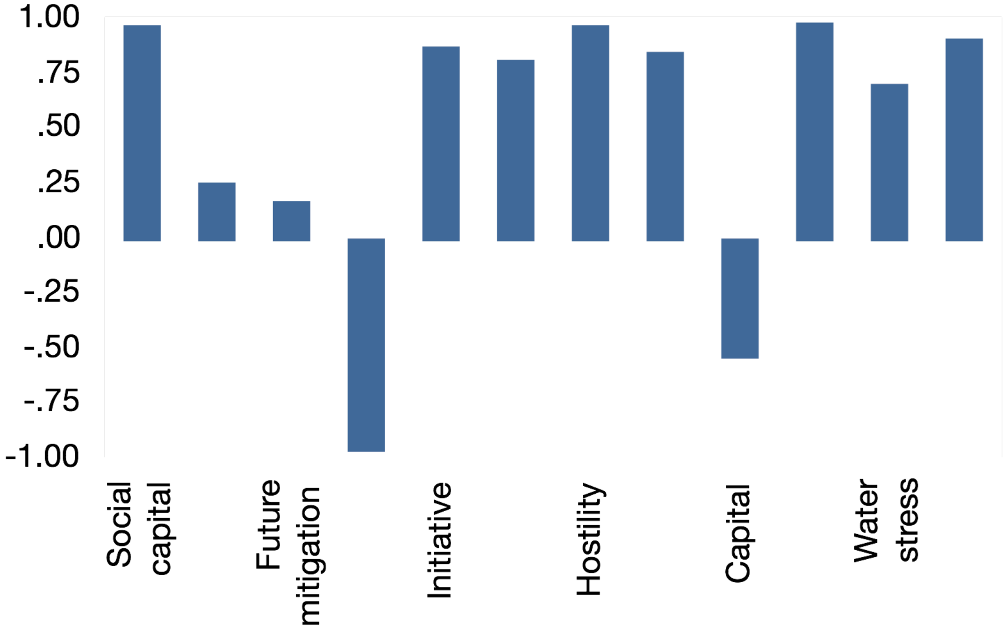


Figure 43: covariance calculated for agent characteristics and complaint frequency, for the SU agent in the +GWB scenario. Note that the values have been normalized to 0.0-1.0.

Figure 44 below shows the same data in a slightly different format (non-normalized) due to the addition of court action data for the -GWB scenario, and some highly variable and probably erroneous data in the samples. Once again, we see that GWI and SU agents are the source of most trouble in the artificial society. Other notable observations include:

i. Negative correlation between water stress and complaint frequency for SU.
ii. Negative correlations between hostility, suspicion, income stress and complaint frequency for SU. The relationship between income stress and complaint frequency is somewhat suspect and may be erroneous.
iii. Positive correlations between happiness and complaint frequency in SU: this is in contrast to the negative correlation between happiness and complaint frequency seen for the +GWB scenario in SU agents.

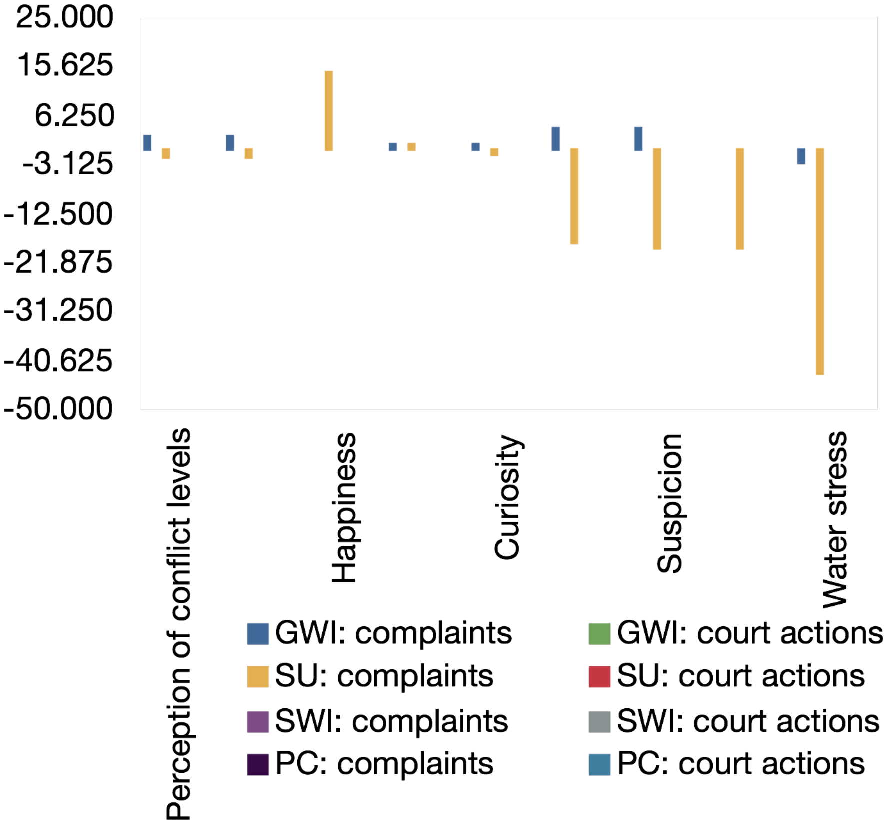


Figure 44: non-normalized covariance between agent characteristics and complaints/court actions, -GWB scenario.

To take a more general perspective, Figure 45 below shows R-squared values for a multiple regression using key agent characteristics selected, against complaints and court actions for each scenario. Some of the notable features of this plot are as follows:

i. The strongest relationships on average are between capital and conflict frequency, suggesting that a significant proportion of the variability in conflict frequency may be due to inter-agent and inter-annual variability in capital reserves.
ii. Weak relationships tend to be seen for happiness, initiative, curiosity and hostility - some of the most key emotional variables for agents.
iii. Complaints in the +GWB scenario appear to have significant variability in strength of relationship across the variables, while court actions see more consistent relationships.

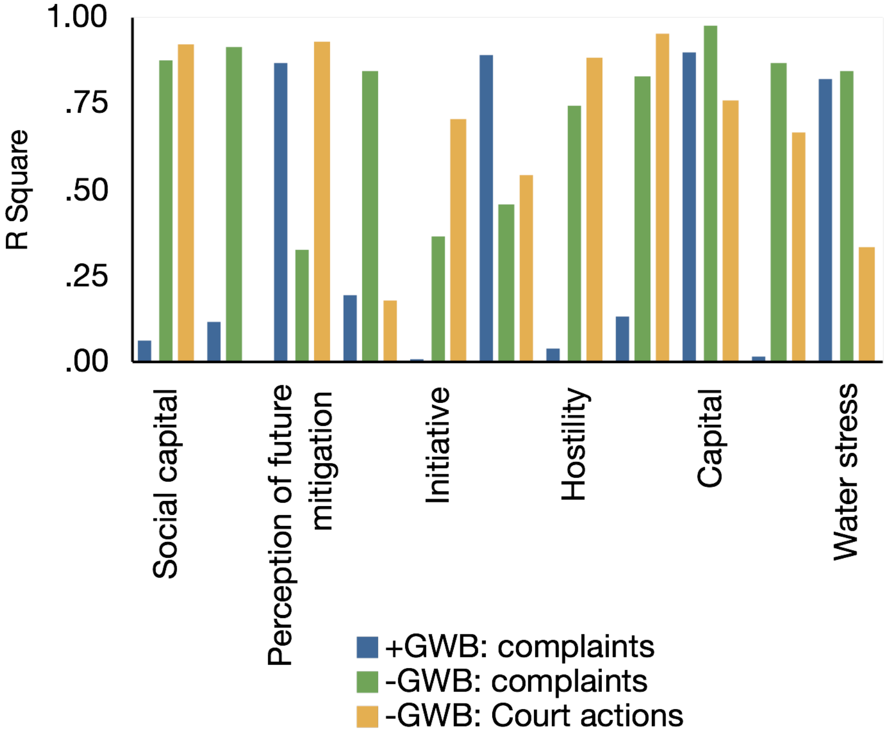


Figure 45: multiple regression of agent characteristics against levels of complaints and court actions in each scenario.

5.2.1.3 … Results Summary 1-C: Influence of agent characteristics on complaints and court actions

In summary, then, a number of key points can be drawn from our regression and covariance-based survey of relationships between some key agent characteristics and conflict event frequency:

1. Across all agents and both scenarios, the financial variables appear to have the strongest relationships with conflict frequency. Higher capital generally equates to fewer complaints and court actions, and higher debt to more complaints and court actions. Interestingly, higher debt appears to have more of an effect on complaint frequency than court action frequency.
2. Relationships between variation in emotional parameters and conflict frequency are decidedly mixed: for example, some agents appear to have inverse relationships between happiness and conflict frequency, other agents strong positive relationships. In other words, correlations are present but are often contradictory and so do not bear up to detailed analysis.
3. Social capital appears to be an important parameter for agents, and appears to be positively correlated with complaint frequency for both GWI and SU agents.

Having examined in some detail possible statistical relationships between agent cognitive parameters, available financial resources and conflict frequency, I now turn back to broader brush metrics. The following plots are simple comparisons of model evolution with and without the ground water banking option activated. Progressive changes in court actions, complaints and bankruptcies are shown against increasing model time, with comparisons between scenarios where appropriate.

Figure 46 below shows, for the +GWB scenario, bankruptcies for those agents that went bankrupt over all the years in the simulation. It is immediately clear that it is mostly SWI agents that went bankrupt. SU agents appear to survive the early years of the simulation without any bankruptcies, but then experience a late surge towards the end. The decrease in bankruptcy frequency for SWI agents toward the mid-part of the simulation is interesting, suggesting that there might be some longer periodicity in financial failures for SWIs not captured by the model's short runtime.

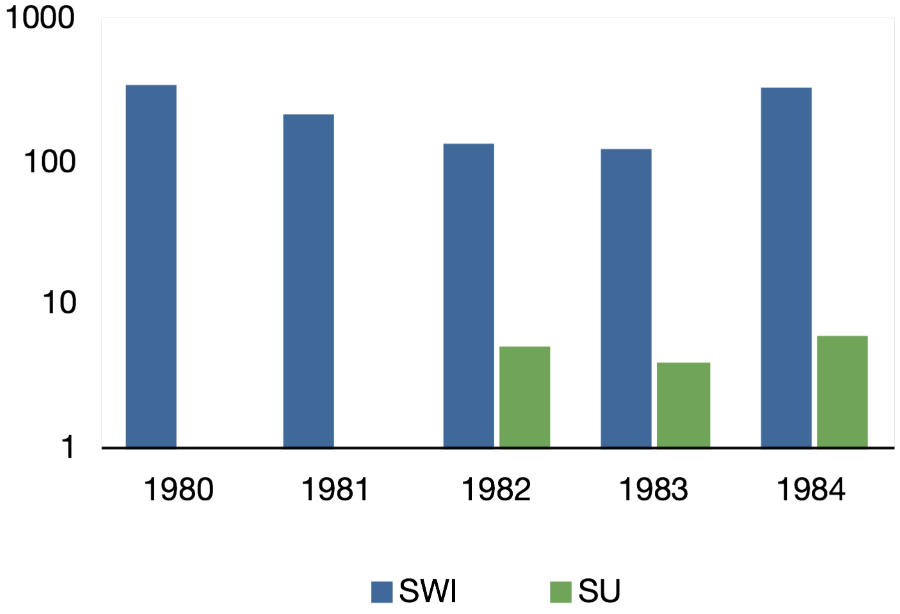


Figure 46: bankruptcies by agent and year in the +GWB scenario.

Figure 47 below, -GWB bankruptcies by year and agent, shows a different picture. Whereas the +GWB scenario bankruptcies were restricted to just two agent types, with one agent type dominating, three agent types undergo financial failures in the -GWB scenario, and GWI agents follow SWI agents closely in inter-annual variation in bankruptcy frequency. SU agents, once again, do not appear to go bankrupt until the latter stages of the simulation.

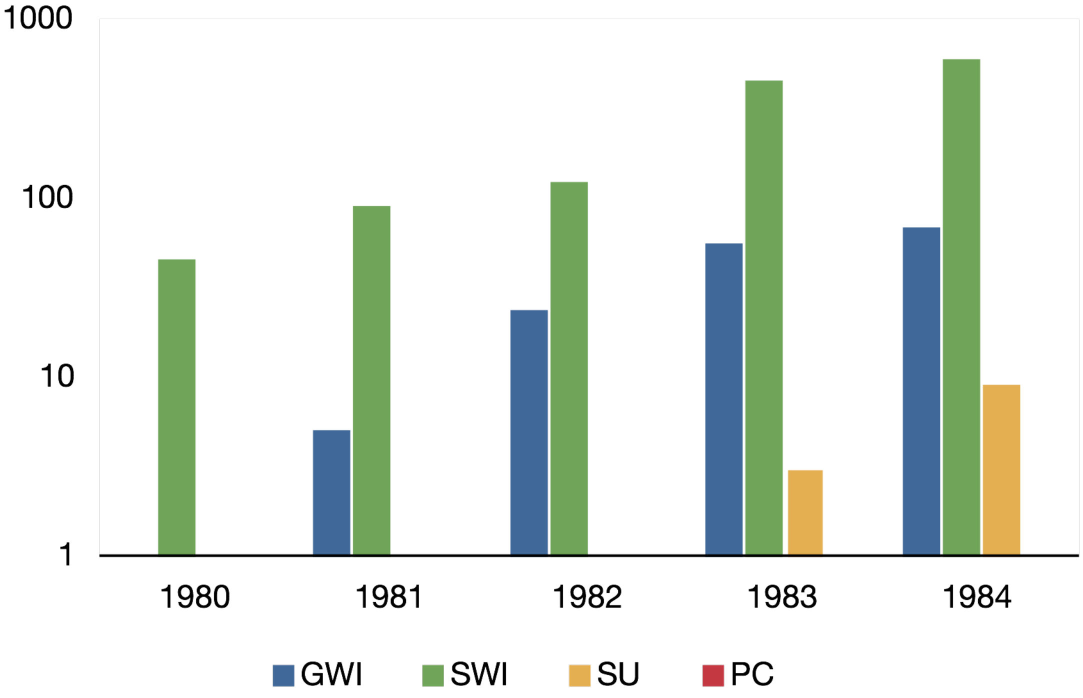


Figure 47: bankruptcies by agent and year, -GWI scenario.

These inter-scenario differences are much clearer in Figure 48 below. In absolute terms, fewer agents go bankrupt in the +GWB scenario than do in the -GWB scenario, but there is some ambiguity in inter-annual variation between the two scenarios. For example, for 1980, 1983 and 1984, SWIs in the +GWB scenario generate fewer bankruptcies than in the -GWB scenario, but this relationship is reversed for 1981 and 1982. Peak levels of bankruptcy for all agents across both scenarios and all years are firmly in the latter part of the simulation and for the -GWB scenario.

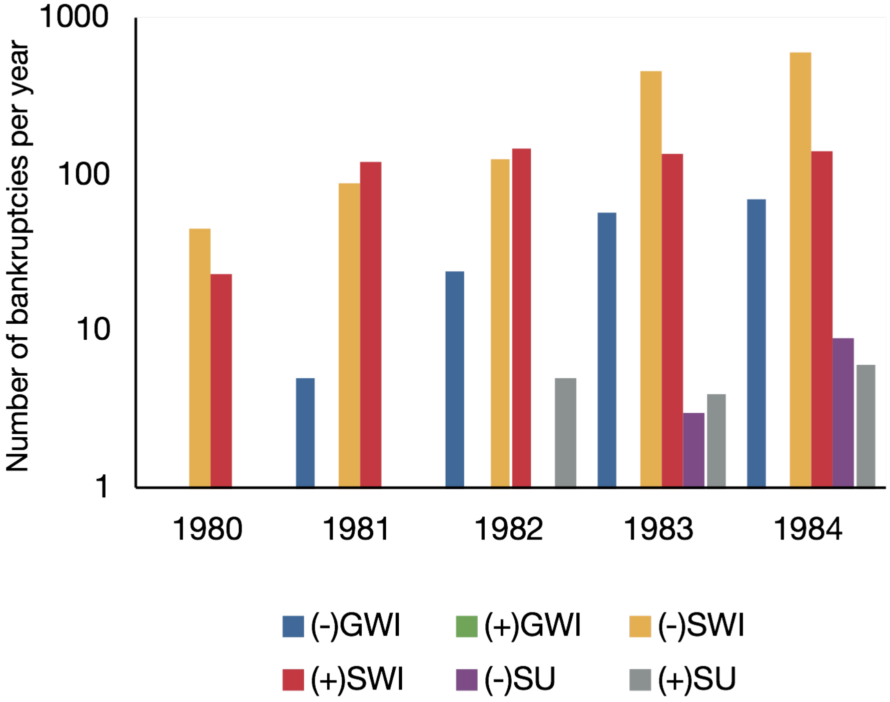


Figure 48: comparison of bankruptcies between scenarios and across agent type.

Figure 49 below shows the progression over time in the numbers of court actions each year. This is only for the -GWB scenario, since no court actions were encountered for the +GWB scenario. The trend is, overall, up: there are more court actions per year in 1984 than there are in 1980. However, the reduction in court action generation in the mid-part of the simulation is interesting, particularly when we remember the similar shaped curve for SWI bankruptcies over the same period - albeit for a different scenario.

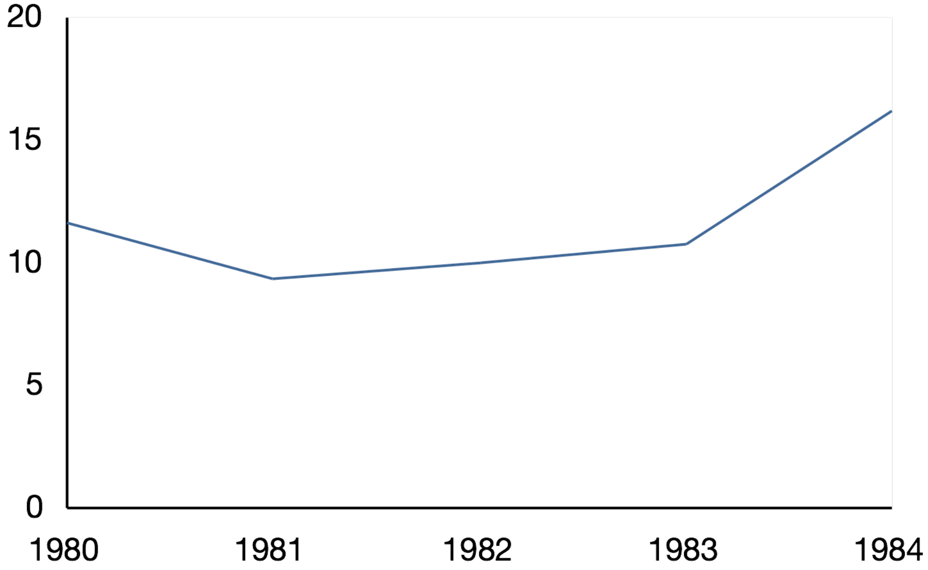


Figure 49: court actions by year of the -GWB scenario simulation.

Figure 50 below displays the variation in bankruptcies over time in an inter-scenario comparison. Nothing significantly new is on offer here, except to show definitively how the -GWB scenario has a steeper gradient of increase in bankruptcies over time and a higher overall level of bankruptcies.

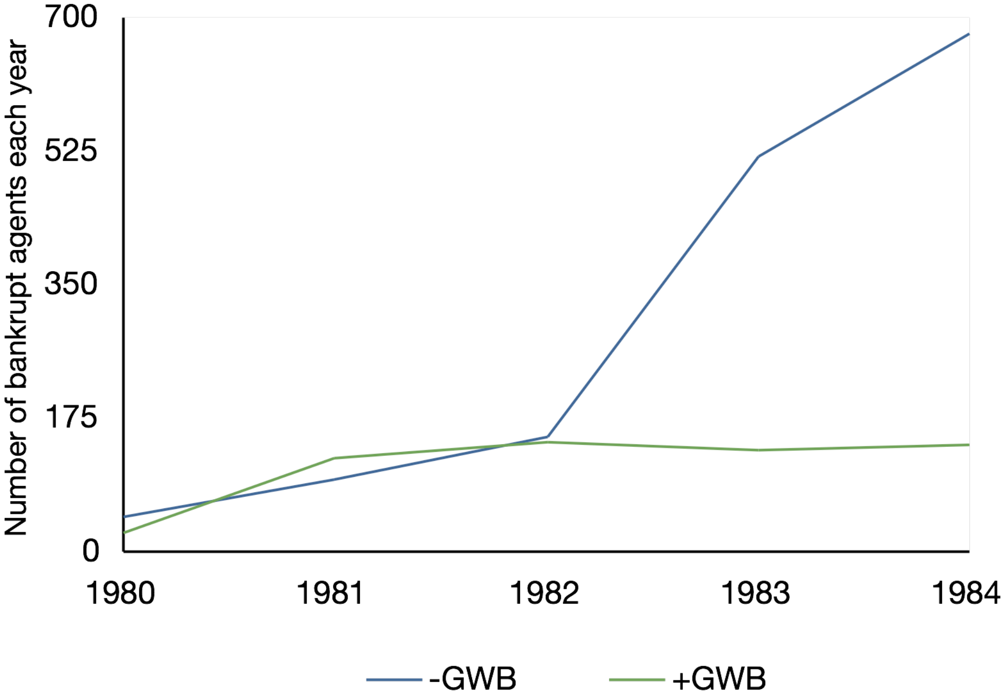


Figure 50: change in annual bankruptcies over time, both scenarios.

Finally, the following series of graphs show the source of court actions and complaints - the agent types which generated the most court actions and complaints each simulation year.

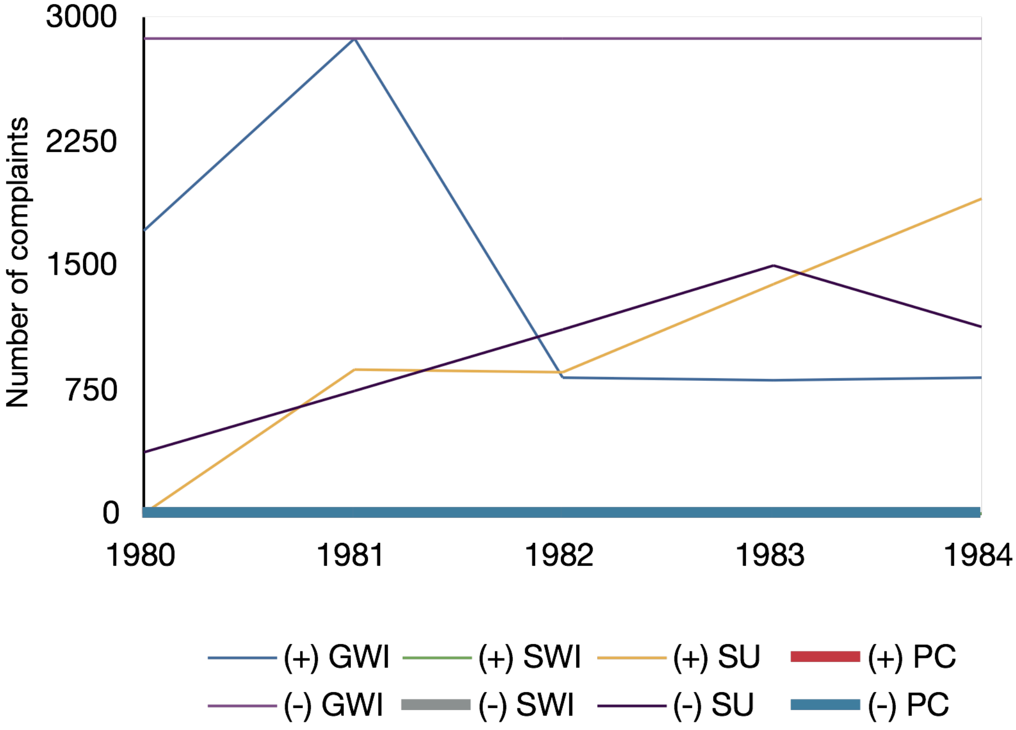


Figure 51: mean complaint frequency per year, for each agent source.

Figure 51 above addresses mean complaint frequency by year for both scenarios. Immediate observations of note include:

i. The constant high generation frequency of the GWI agents in the -GWB scenario, contrasted with their more variable generation frequency of the +GWB scenario.
ii. The steady increase in SU complaints over time for both the + and - scenarios, with the peak achieved in the +GWB scenario.
iii. The flat curves for both SWI and PC agents in both scenarios.

Figure 52 below depicts mean court action generation frequency for the only scenario that generated court actions, -GWB.

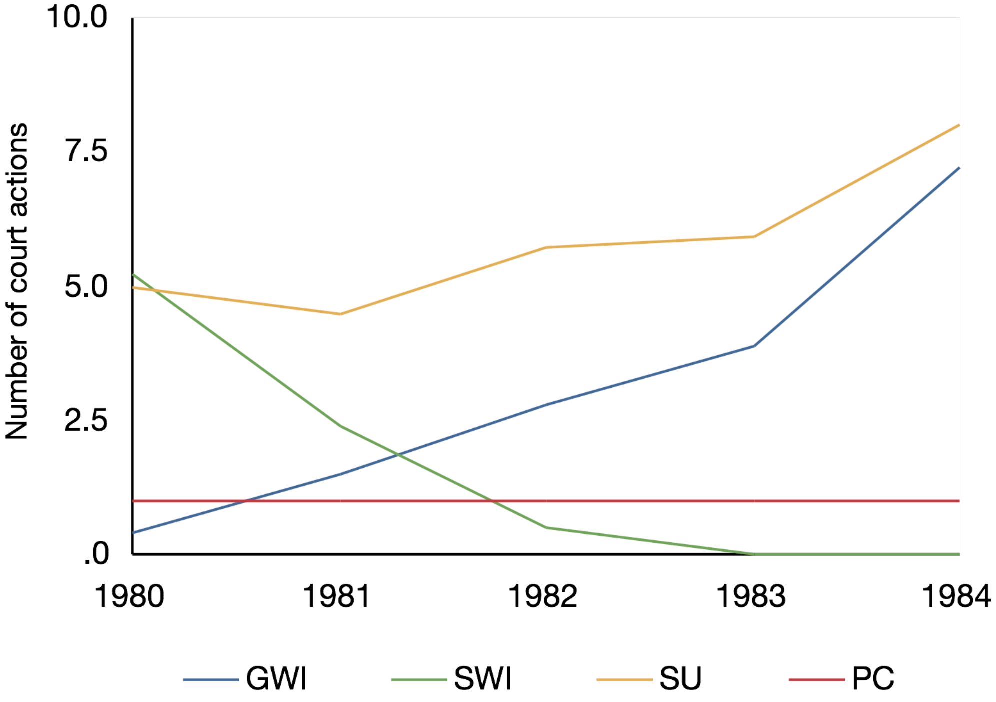


Figure 52: mean court actions by year and agent source, -GWB scenario.

Immediate observations of note include:

1. Steady upward trend for both SU and GWI agents through the simulation.
2. Steady downward trend for SWI agents through the simulation.
3. Constant but very low generation rate from PC throughout the simulation.

Two key indicators, water stress and income stress, represented catch-all variables impacted by a number of different agent decisions and changes in the agent's external environment. These indicators enjoy the most frequent implementation of fuzzy logic of any parameters in the model. The significance of emphasizing fuzzy logic with the stress variables is that these variables represent the closest thing to an overall indicator metric for agent 'state of mind', i.e. the stress variables draw on the largest rulesets and are the most sensitive to changes in relevant internal and external conditions.

If an agent has a high water stress, for example, it generally indicates that a number of water-related conditions both internal and external to the agent are not going well. Note that, unfortunately, there is no universal metric for 'going well'. Given that the irrigator agents are interested in increasing water levels in the canals and the power company agent is interested in increasing water levels in the river (to feed its run-of-the-river dams and keep electricity generation rates up), different agents can be stressed in opposite directions by the very same environmental condition.

Given the 'catch-all' nature of these variables, it is important to understand, in addition to how these indicators may have been related (or not) to overall levels of conflict, how these indicators varied over time for each agent. Exploring the shape of these curves might help us explain other trends in the data and overall system behavior. Figures 53 and 54 below shows plots for both scenarios, indicating how water stress and income stress vary over the 5 year model runtime (data averaged across all runs, all agents of the same type, within each scenario). 100% stress for a given scenario would correspond to all agents experiencing 100.0 values in that particular form of stress (the maximum level for all stress variables). Note that a negative value for stress corresponds to a recurrence of conditions favorable to reducing stress. Once the agent is entirely unstressed (i.e. percentage reaches 0), the time steps for which conditions continue to be actively not stressful force the stress value into negative values (i.e. if conditions go on to cause neither an increase or decrease in stress, then the stress value stays at 0). This is intended to convey the concept of conditions being generally favorable or unfavorable for a particular agent type; a simple 0 value for stress would not convey the same information. Figure 53, an inter-scenario comparison for water stress, has some notable features:

i. Across both scenarios, water stress for SWIs increases over time. Water stress is generally highest for these agents in the latter part of the simulation, although the peak stress for SWIs in the +GWB scenario is actually seen in 1981.
ii. Stress for GWIs is highest, for both scenarios, in the early years of the simulation. Stress for these agents drops to 0 or negative stress over time.
iii. Water stress for SU and PC agents is either zero or negative throughout the simulation, with stress either remaining static and negative or becoming increasingly negative over time.
iv. The static state of PC and SU agents for the -GWB scenario is somewhat puzzling, when we remember that SU agents were responsible for a significant proportion of complaints in both scenarios. This suggest either no clear link between water stress and the likelihood of the agent complaining, or some other confounding variable.

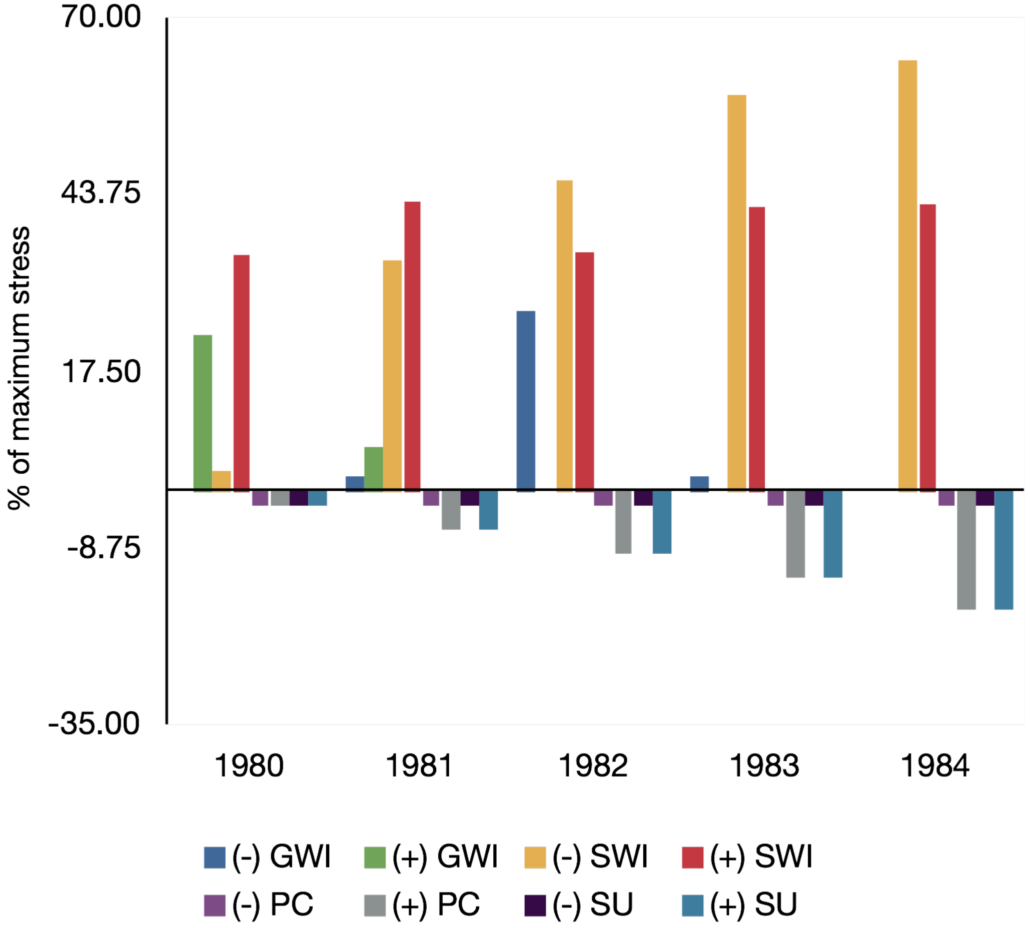


Figure 53: change in water stress over time, by agent and scenario.

The same graph produced for income stress shows a similar overall appearance. Income stress for SWI agents in both scenarios increases over time, although it increases more slowly and achieves lower peaks than for water stress. For all other agents, however, income stress decreases into negative values, or remains static, over time. Highest values of stress for the SWI agents are in the -GWB scenario. For other agents there appears to be little difference in the stress response of the agent given different ground water banking options (but remember that PC and SU agents were not allowed to participate in the bank).

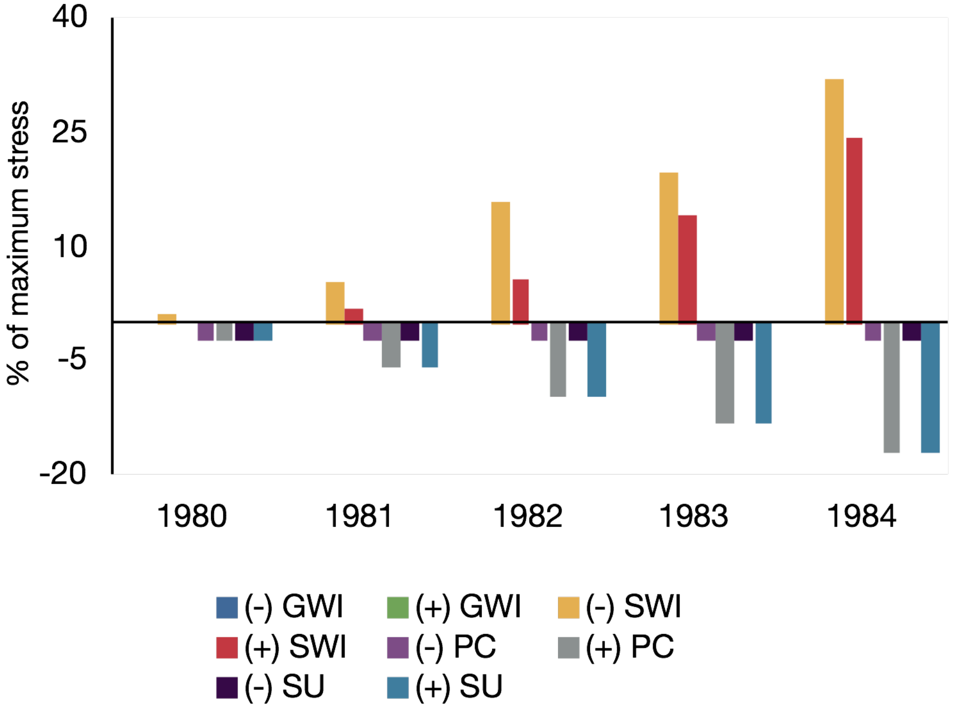


Figure 54: change in income stress over time, by agent and scenario.

In summary, then, my exploration of court action, bankruptcy and agent stress changes over time has yielded the following key observations:

5.2.1.4 ... Results Summary 1-D: conflicts and stress

1. Fewer agents go bankrupt in the +GWB scenario compared with the -GWB scenario.
2. Bankruptcy figures for both scenarios are dominated by the SWI agents, and the number of SWI bankruptcies generally increases during the simulation run. This is generally true of all other agents who experience bankruptcies.
3. Court action frequency generally increases over time in the -GWB scenario (remember that no court actions were generated in the +GWB scenario).
4. The SWI and PC agents generate little or no conflict in the +GWB scenario, but constant or declining levels of conflict in the -GWB scenario.
5. The SU and GWI agents are responsible for the bulk of the complaint and court action generation in both scenarios.
6. The -GWB scenario sees the agents in their most stressed state, for both income and water stress.
7. SWI agents experience the most water and income stress out of all agents, in both scenarios.
8. Both water and income stress tend to increase over time for SWI agents, but decrease or remain static for most other agents.

A final area of interest is in the exploration of environmental conditions (reach flows, spring flows and canal flows) relative to conflict frequency and severity. So far we have mostly only explored internal agent conditions (such as agent happiness) and more broad societal conditions (such as level of bankruptcies across an agent population). External environmental variables are conceptually likely to have a very strong influence on agent behavior and internal state: the amount of water in a canal dictates how much is available to each surface water irrigator agent (as long as it is the same as or less than the agent's entitlement according to how many shares it owns in the canal). The amount of water available to each agent will partly determine what type of crop and how much acreage is planted. The type of crop, acreage and availability of irrigation water will be strong influences on the yield that year and the amount of income the agent receives. If there is a major drought, and little water is in the system, many agents will experience severe economic stress (translating into financial stress).

Unfortunately, while data was written to file on a regular basis for reach flows, reach diversions and canal volumes, in both experiments an I/O problem meant that the data was significantly corrupted and consequently unusable. In the analysis and discussion that follows, this fact must be born in mind: however good the explanation for a link between an internal agent variable and an external societal metric (such as complaint frequency), it may well be overshadowed by a strong, and unfortunately unknown environmental forcer. The flaw that led to the data corruption was addressed in work on the AlbAgent model.

5.2.2 ... AlbAgent[1]

As for the GWBSIM results, I present the results of AlbAgent experimentation with the intention of supporting or denying the major hypothesis - although I will not explicitly treat the hypotheses in this section. The results are grouped as follows:

1. Time series of conflict
2. Performance of the ground water bank
3. Comparisons between state of the aquifer and various internal and external agent variables, including conflict
4. Covariance between select internal variables of agents and external societal conflict
5. Correlations between variations in climatic parameterization and conflict outcomes
6. Correlations between variations in institutional parameterization and conflict outcomes

I use the time series to show how the different scenarios performed in terms of total conflict in the system. It is useful to know which scenarios were the best performing (where 'best' equates to the system with the lowest levels of conflict), since this provides a point of departure for later discussions attempting causal linkages between agent/environmental variables and conflict. I report on the ground water bank's performance for a similar reason: from the AlbAgent parameterization table discussed

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[1] Standard deviations are not included unless they were significant enough to warrant discussion in the text

under the Parameterization section, we know that scenarios are either low, moderate or high on institutional or climatic scales. It is possible then to make some preliminary associations between qualitative 'change state' and the bank's performance. I calculate correlation coefficients between a number of internal agent variables and overall societal conflict to look for any potential for causality. For example, internal stress may both be a product of wider societal conflict as well as a cause; it is not trivial to determine which came first, and by calculating correlation coefficients I may be able to make a better determination. Finally, I examine correlations between initial climatic/institutional parameterization and overall conflict outcomes to determine whether the 'state of change' in each scenario may be having a strong influence on the level of conflict in the system.

Conflict in the system

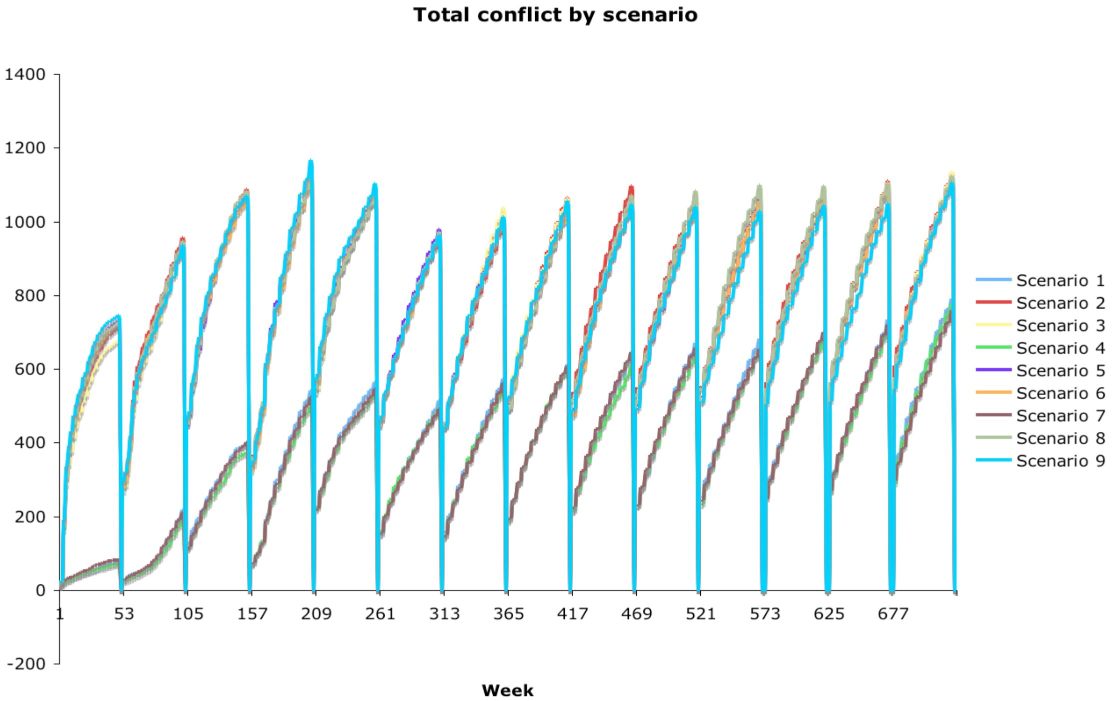


Figure 55: total level of conflict by scenario (number of individual conflict events over time)

Figure 55 shows a number of key features of conflict dynamics (note that the Y axis is number of conflict events, with extra weighting for formal complaints over informal complaints). All scenarios have clear annual periodicity, with the conflict peak achieved just before the new year, and all scenarios zeroing out their conflict in the new year. Most scenarios show a steady increase in conflict over time, particularly those scenarios with less overall conflict relative to other scenarios. Importantly, the scenarios are grouped by frequency of conflict: scenarios 2, 3, 5, 6, 8 and 9 suffer much higher conflict frequencies that scenarios 1, 4 and 7. The more severely conflicted scenarios peak in conflict within the first 5 years of the simulation, thereafter dropping off sharply before slowly climbing back up. In no scenario does conflict actually decrease over time. Most importantly, the scenarios with the lowest levels of conflict were those that did not include ground water banking as an option for agents. Not shown on the graphic is the fact that the system did not achieve the highest severity of conflict in any scenario, since the conflicts were entirely made up of formal and informal conflicts: no protests (the AlbAgent equivalent of GWBSIM court actions, in terms of severity) were encountered in any scenario.

Figure 56 compares the same total conflict data against a ‘change index’. Scenario data for average conflict were plotted against their degree of change index, and all entries with a single index were themselves averaged.

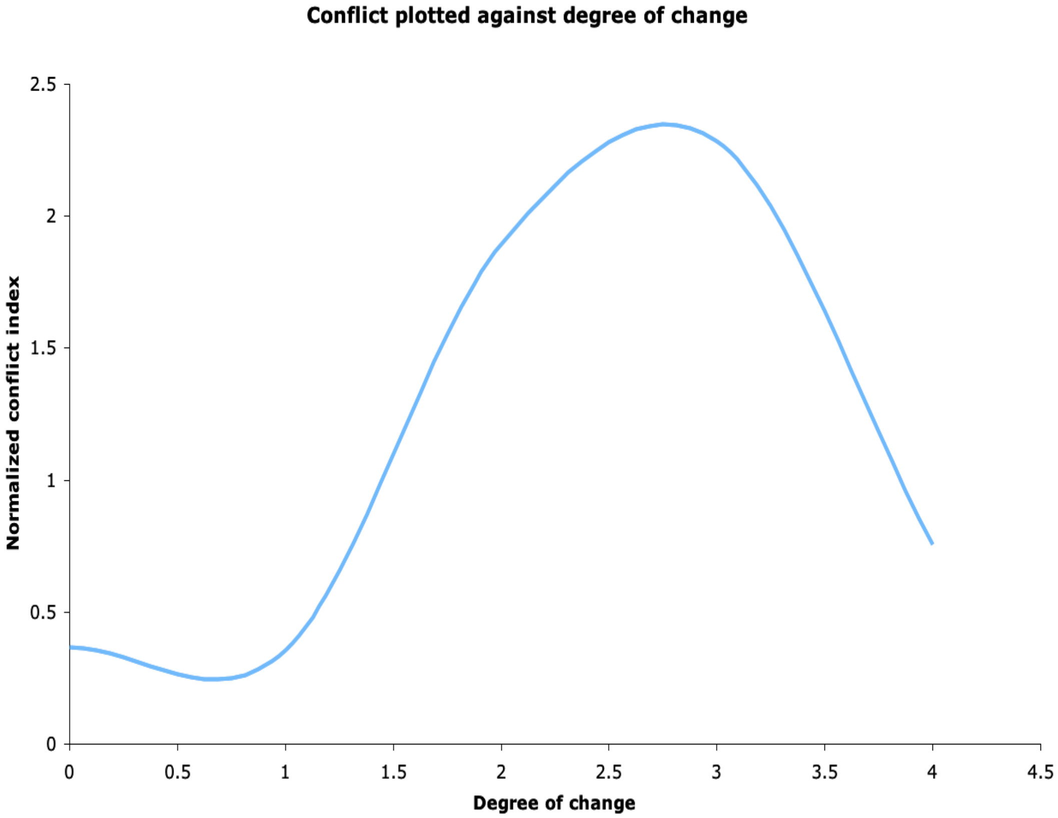


Figure 56: comparing a normalized conflict index with the degree of change experienced by scenarios; note that the degree of change is from no change (0) to maximum change (4). Also note that conflict index is normalized from 0.0 (no conflict) to 3.0 (maximum conflict).

The most interesting feature of the graphic is that despite the general indications that degree of change might be positively correlated with conflict, the actual comparative trace follows a distinctly different pattern: the highest levels of conflict are associated with moderate levels of change. This suggests that it is the type of change rather than the degree of change that is important. This is underlined by the fact that the highest degree of change (close to 4) experiences some of the lowest levels of conflict.

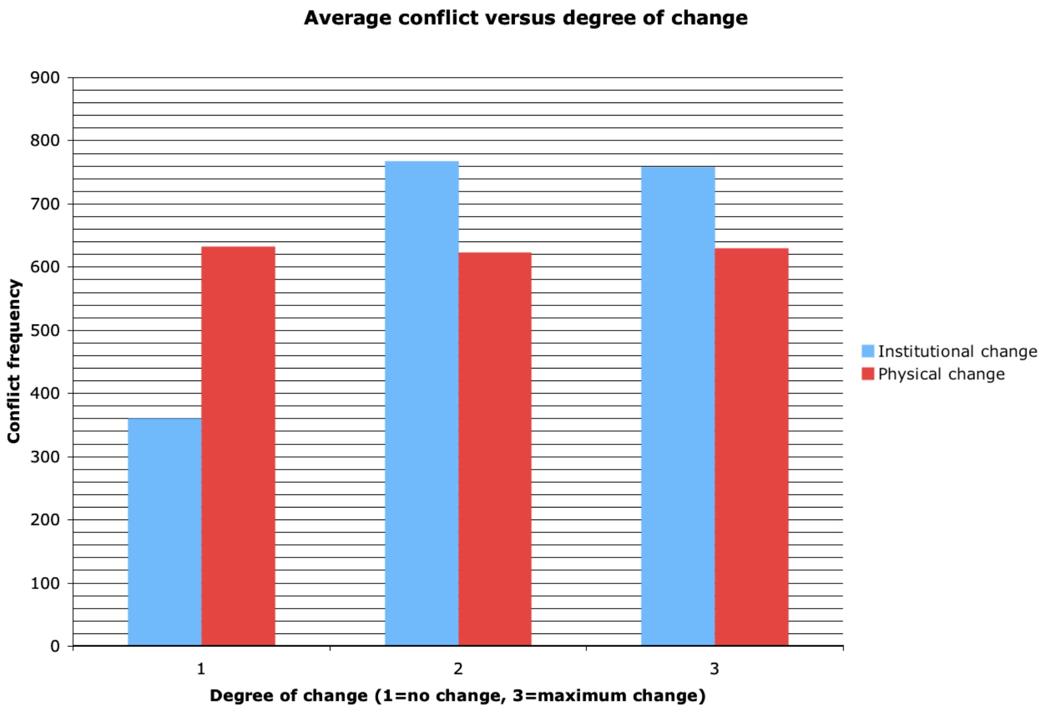


Figure 57: comparing degree of institutional and physical change with conflict frequency.

The figure above (Figure 57) breaks down the data into specific types of change, and in so doing conveys four important bits of information. The first is that institutional change sees much stronger conflict responses than physical (climatic) change. Conflict drops slightly as climate change increases, but the change is subtle and essentially there is little variation. Conflict increases dramatically as institutional change increases, but tapers off slightly at the highest degree of institutional change. The second point is that the peaks of conflict under institutional and physical change do not coincide with the same degree of change. We see the highest level of conflict for institutional change when that change is only moderate, and the highest level of conflict for physical change under the no physical change scenario. This brings us to the third point, that conflict exists in the system with or without change: the no-change scenarios for both physical and institutional dimensions show conflict. Finally, we see that ground water banking (only active at degrees 2 and 3 of institutional change) was accompanied by higher conflict relative to those scenarios with no ground water banking.

5.2.2.1 … Results Summary 2-A: conflict in the system

In summary, then, the conflict results for the system are as follows:

1. All scenarios have annual periodicity in conflict.
2. Most scenarios show an increase in conflict with time.
3. Those scenarios with ground water banking all experienced higher conflict than those scenarios without ground water banking.

4. Scenarios with more severe conflict showed peaks in the first 25-40% of the simulation, whereas the scenarios with the lowest conflict peaked at the end of the simulation.
5. No acute conflict was experienced by any scenario.
6. Increases in institutional change were generally accompanied by significant increases in conflict frequency. Increases in physical change were not accompanied by significant increases or decreases in conflict frequency.
7. Peaks of conflict occur when institutional and physical change are at different degrees.
8. Conflict was experienced by the system even without any sort of change, physical or institutional.

Bank performance

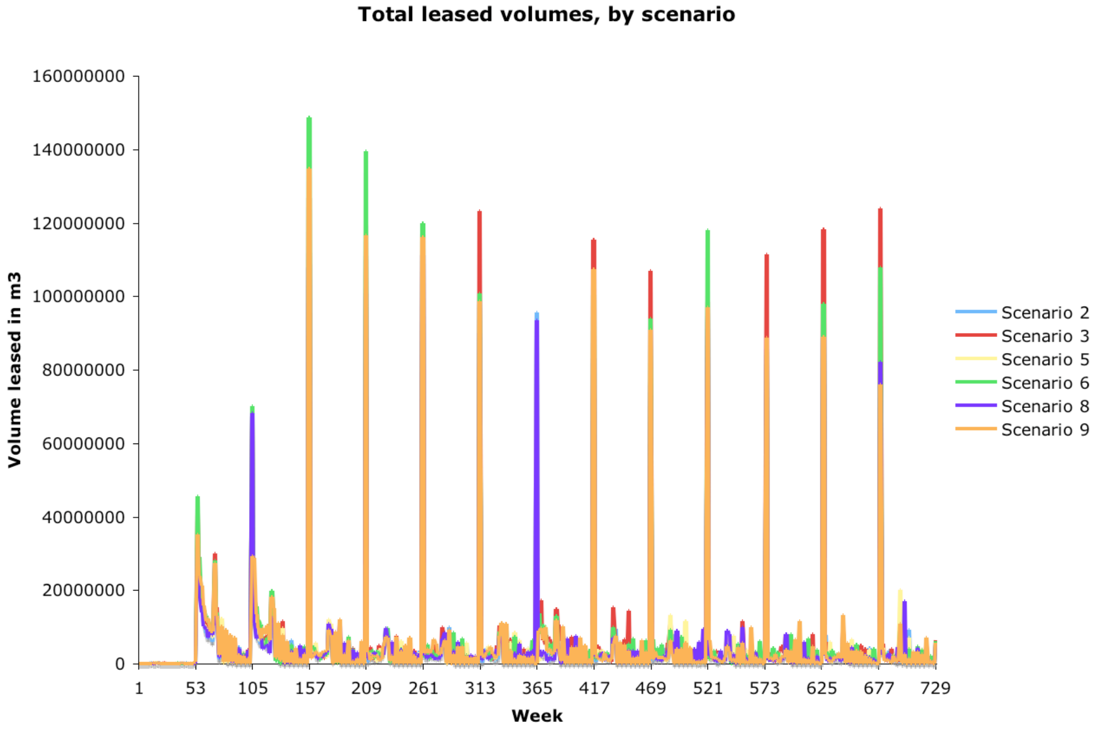


Figure 58: volumes of water in meters cubed, leased from the bank over time, for each scenario in which ground water banking was activated.

Figure 58 above shows that bank performance (in terms of leasing) was generally good beyond the first two years of simulation. The highest lease volumes across the scenarios occurred in the first five years of the simulation, with steady decreases for five years thereafter and then fluctuation across all scenarios resembling something akin to Epstein's punctuated equilibrium (Epstein 2002). Scenario 6 experienced the highest peak in lease volume, but as the Figures below show, did not enjoy the highest average or highest overall volume. Beyond the first few weeks of each year, lease volumes - and by extension, participation in leasing - dropped off precipitously. Very much smaller lease volumes were seen during the remainder of each year, but lease volumes rarely drop to zero. Considerable variance can be seen across all scenarios: Scenario 8, for example, sees a few peaks of activity separated by many years of below average leasing. Scenario 9 shows the opposite, with many years of high levels of activity followed by a single slump year.

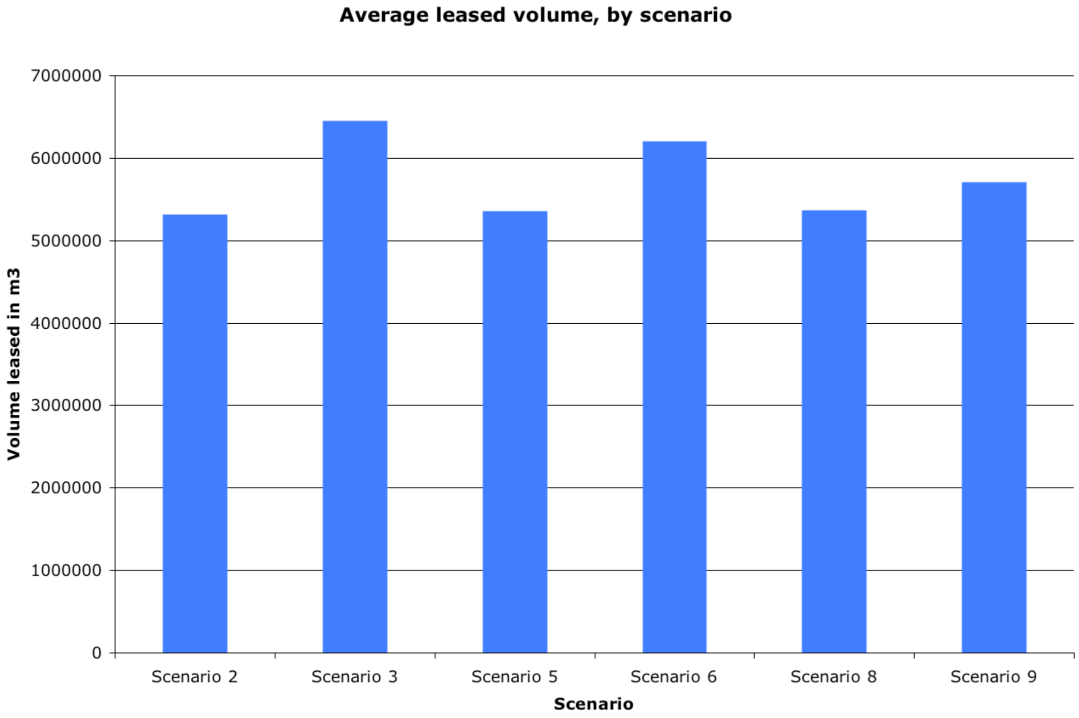


Figure 59: average lease volume per week, by scenario

Figure 59 above shows small, but statistically significant variation between scenarios in terms of lease volume (standard deviations were generally too small to be usefully plotted). Scenario 3, with high levels of institutional change but no physical change, shows the highest average lease volume. Interestingly, there appears to be a neat relation between degree of institutional change and average volume leased: all the moderate change scenarios (2, 5 and 8) show less average volumes than the extreme institutional change scenarios (3, 6 and 9).

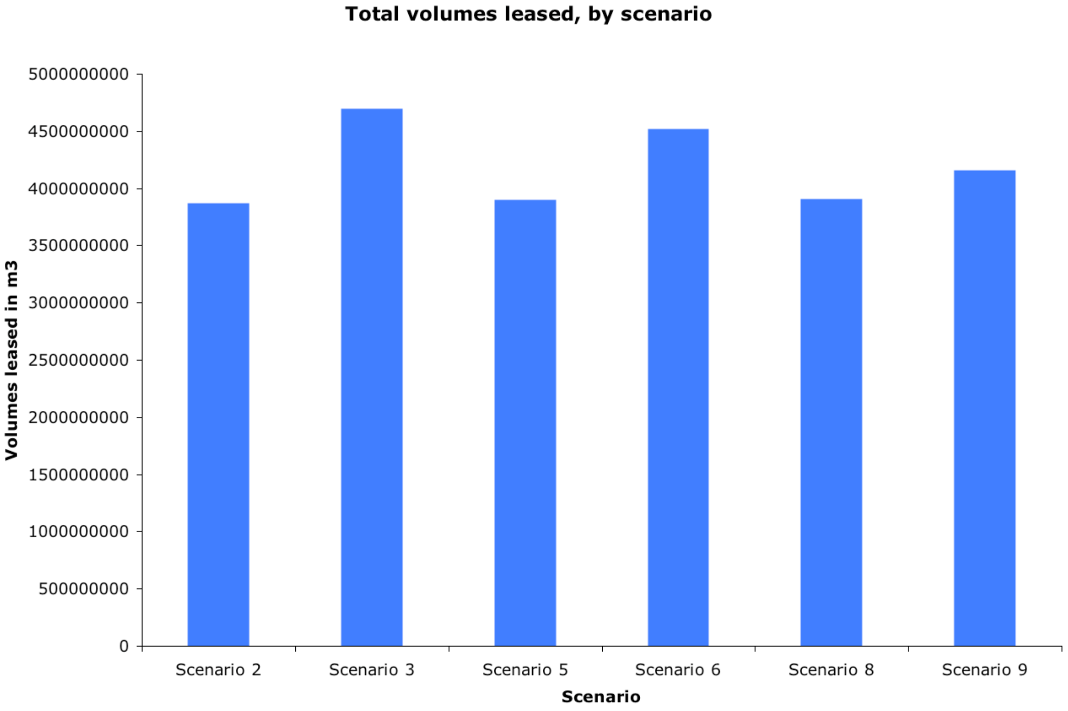


Figure 60: total volumes leased under each scenario

Figure 60 above simply reinforces the fact that Scenario 2 was the most voluminous case for volumes leased, as well as the bifurcation in lease volumes between moderate and extreme institutional change scenarios.

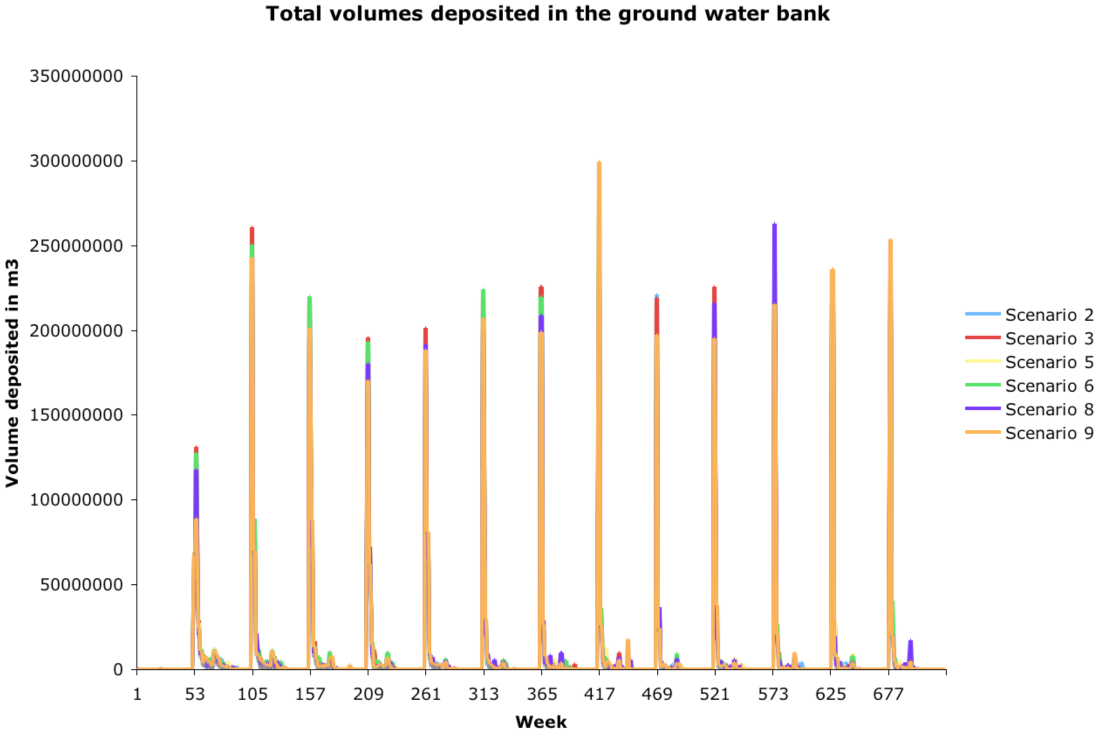


Figure 61: volumes deposited in the ground water bank, by scenario, over time

The case for deposits is somewhat different. Instead of seeing higher transaction volumes initially, deposits show a somewhat variable but weak trend towards increasing over time (after initial peaks for some scenarios). This finding of generally trend-less data for banking transactions applies to both deposit and lease data. Scenario 9 displays the peak deposit volume. As for the lease data, activity at the beginning of each year is high but tapers off.

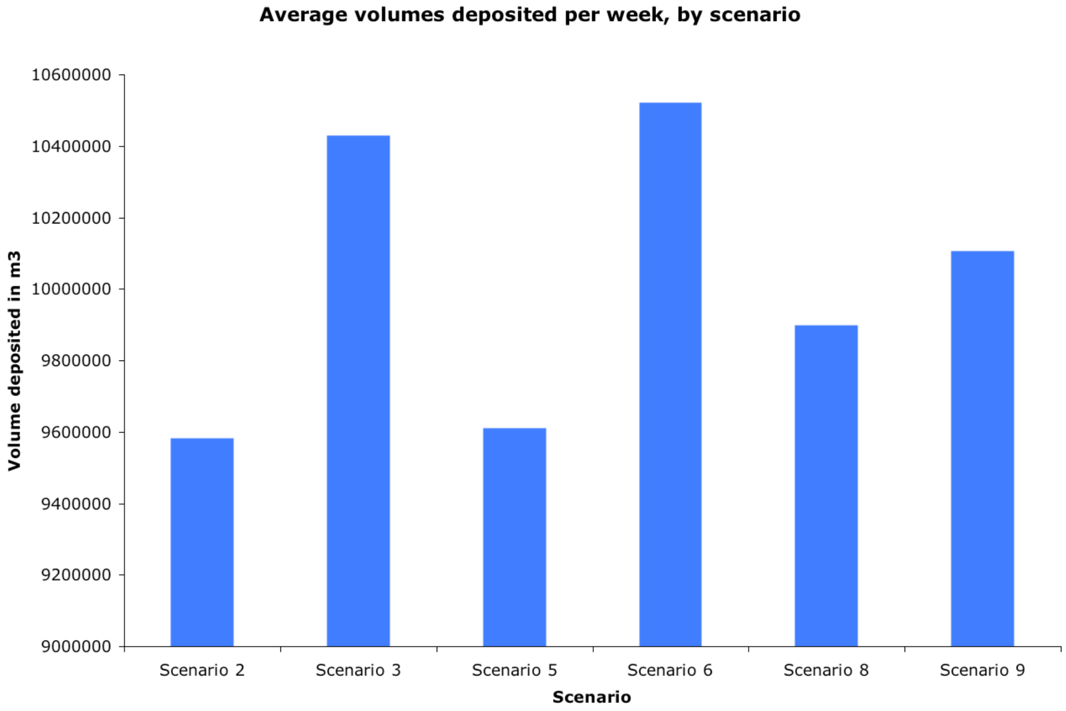


Figure 62: average volumes deposited per week, by scenario

Figure 62 above shows that Scenario 6 had the highest average deposit per week, while Scenarios 2 and 5 the lowest. The difference is a little less significant, but in general we again see that the highest degrees of institutional change tend to be accompanied by high volumes deposited in the aquifer, and vice versa for scenarios with moderate degrees of institutional change.

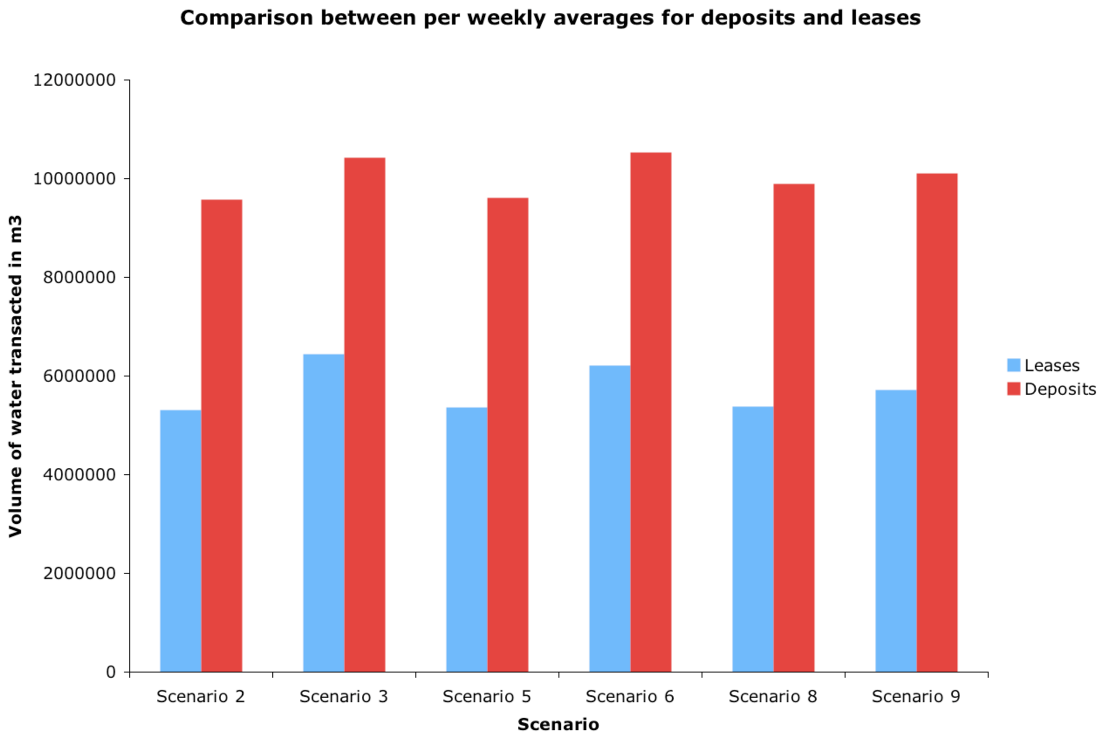


Figure 63: comparing average weekly transaction volumes

Figure 63 above shows that deposits and leases, when considered together, show seriously unbalanced performance for the ground water bank. As we saw in GWBSIM, leases are again outweighed by deposits, sometimes 2:1. Interestingly, however, the change in peak height between scenarios shows a similar pattern for deposits as for leases, suggesting that leases and deposits track each other within any one scenario, i.e. there may be some relation (uni- or bi-directional causality) connecting volumes of lease transactions to deposit transactions. Scenarios 3 and 6 display the highest average activity of all the scenarios, leases being slightly higher and deposits slightly lower in volume for Scenario 3.

5.2.2.2 ... Results Summary 2-B: performance of the ground water bank

In summary, then, our examination of the ground water banking performance data has shown the following:

1. The bank was clearly functional across all years of the scenarios that simulated ground water banking.
2. The highest lease volumes across all scenarios were encountered in the first five years of the simulation, with considerable fluctuation in lease volumes thereafter.
3. The highest lease volumes in each year were encountered at the beginning of each year, followed by much more minor peaks later in the year.
4. Scenario 3 shows the highest average and total lease volumes.

5. Scenarios with the highest degrees of institutional change showed the highest lease volumes, vice versa for scenarios with only moderate degrees of institutional change.
6. Neither deposits or leases show any clear increasing or decreasing trend, but there is a possible trend toward increasing volumes over time in the deposit data.
7. Deposits show less variability than leases, but the same intra-annual pattern of variability.
8. Scenario 6 experienced the highest average and total deposit volumes.
9. Deposits greatly exceeded leases in average and total volumes.
10. Variation in lease volumes between scenarios follows the same broad pattern seen in inter-scenario deposit volume variation.

State of the Aquifer

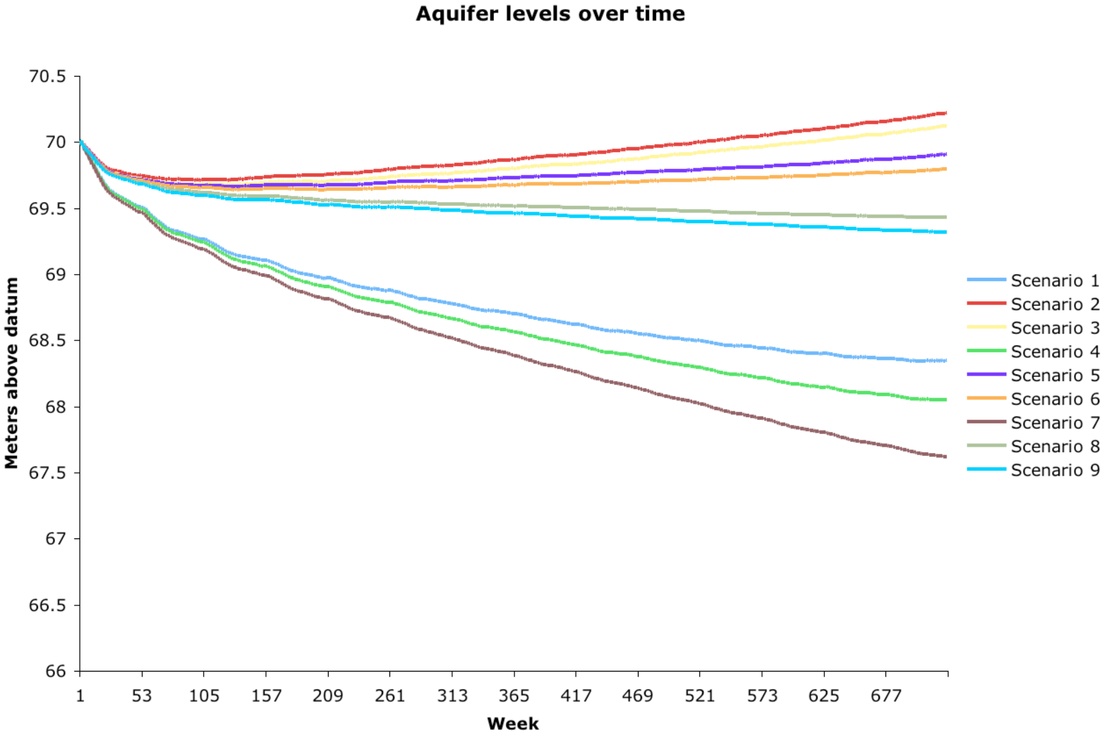


Figure 64: changing aquifer levels, in meters above datum, over time and organized by scenario.

Figure 64 above shows clear differences between scenarios with regard to whether or not the use of water during the scenario led to sustainable treatment of the aquifer. For the purposes of this analysis, ‘sustainable’ aquifer use is that which does not deplete the aquifer (reduce the level of water in the aquifer) over time. Not surprisingly, ‘unsustainable’ aquifer use is that which causes depletion in the aquifer. Sustainable scenarios include 2, 3, 5 and 6. Unsustainable scenarios include 1, 4, 7, 8 and 9. All scenarios show the same initial decrease in levels for the first half-year of the simulation; thereafter the sustainable scenarios stabilize and start to increase water levels at a reasonably steady rate until the end of the simulation. The unsustainable scenarios show slightly more fluctuation, but in general also a steady rate of decrease over time. The best performing scenario in terms of sustainability is Scenario 2 (with no climatic change and only moderate institutional change).

Similar data, but presented in terms of snapshots of the aquifer grid after completing a typical run for Scenarios 1, 5 and 9, emphasize that the no institutional change scenario results in a worsened aquifer state, while the maximum institutional change results in an improved aquifer state. The results are not exactly impressive, however: few of the grid cells change sufficient to shift their classification. The change is most pronounced in the areas where depletion was already marked (red shaded cells).

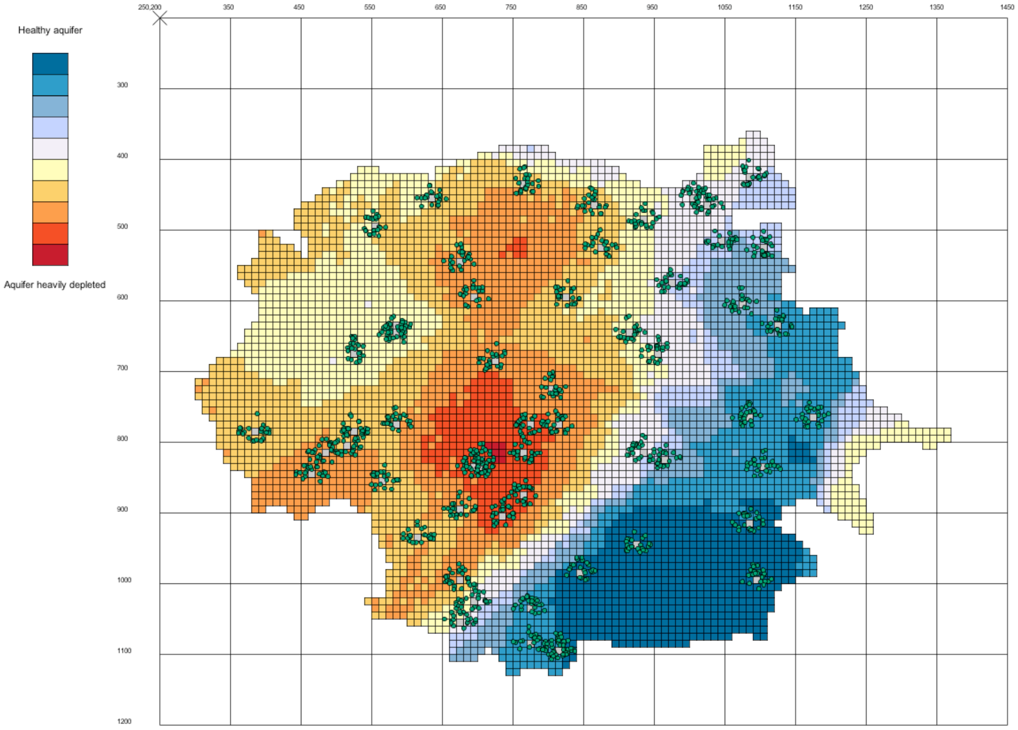


Figure 65: state of the aquifer in 2014 after completing a typical run of the a 'no institutional change' scenario (Scenario 1). Note the scale is from ***more depleted*** *(red shades) to* ***less depleted*** *(blue shades) - ignore the existing scale labels.*

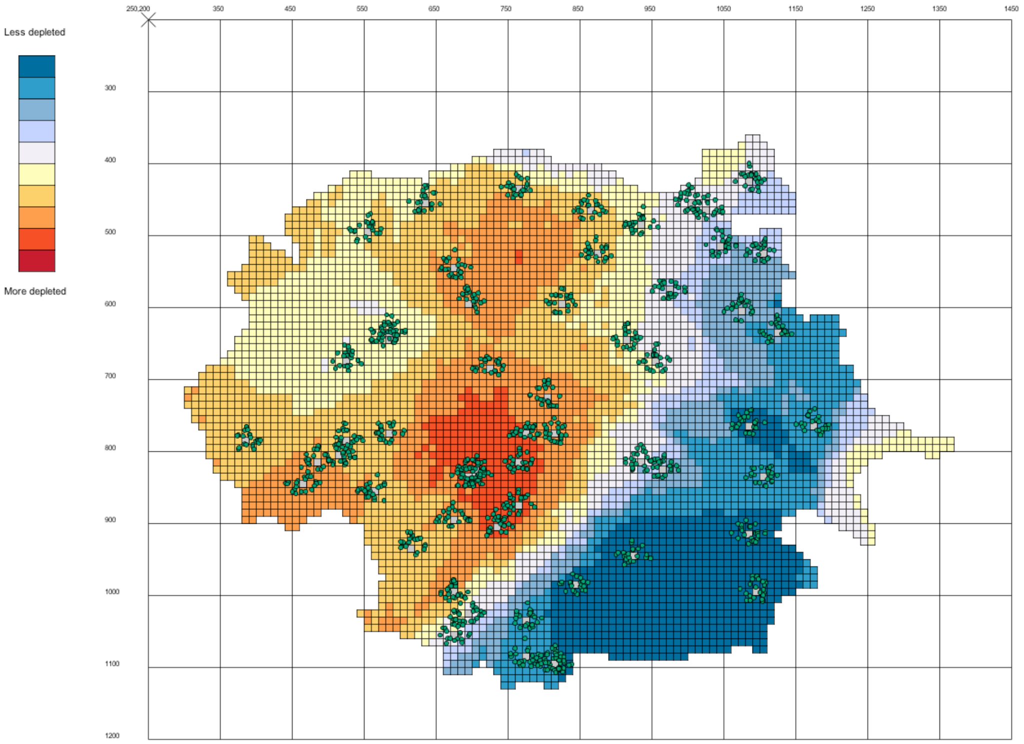


Figure 66: state of the aquifer in 2014 after completing a typical run of 'moderate institutional and climatic change' (Scenario 5). Note the scale is from ***more depleted*** *(red shades) to* ***less depleted*** *(blue shades) - ignore the existing scale labels.*

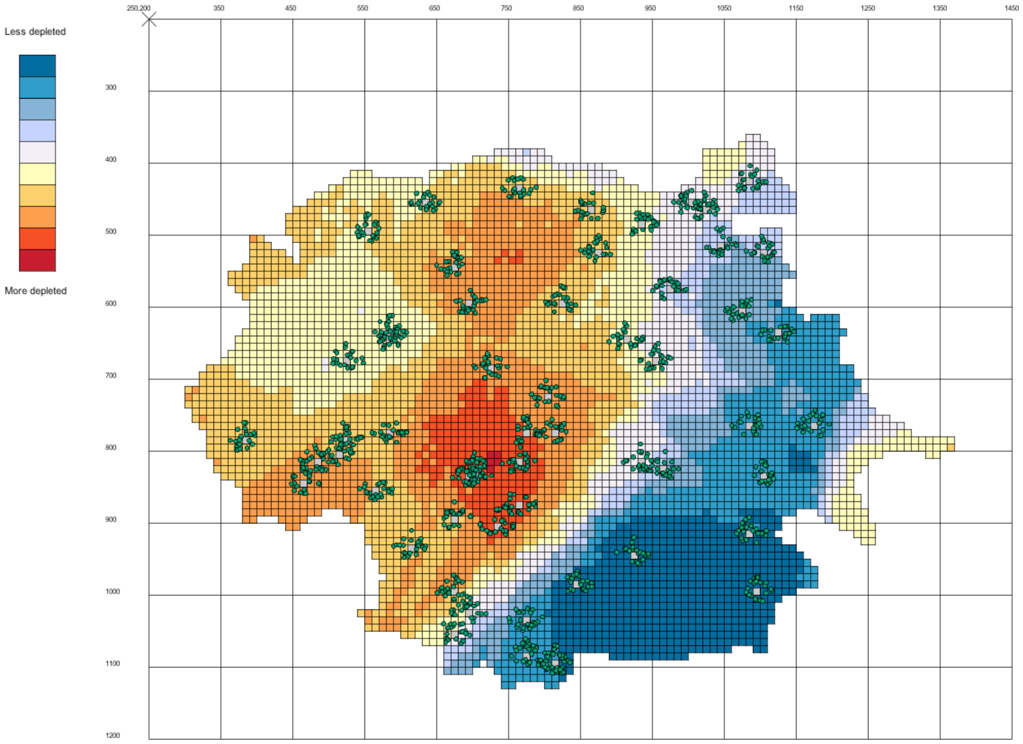


Figure 67: state of the aquifer in 2014 after completing a typical run of maximum institutional and climatic change (Scenario 9). Note the scale is from ***more depleted*** *(red shades) to* ***less depleted*** *(blue shades) - ignore the existing scale labels.*

Correlating GWB transaction activity with variation in aquifer levels suggests there is no strong relationship between aquifer water levels and the intensity of transaction activity through the bank (see Figure 68, below).

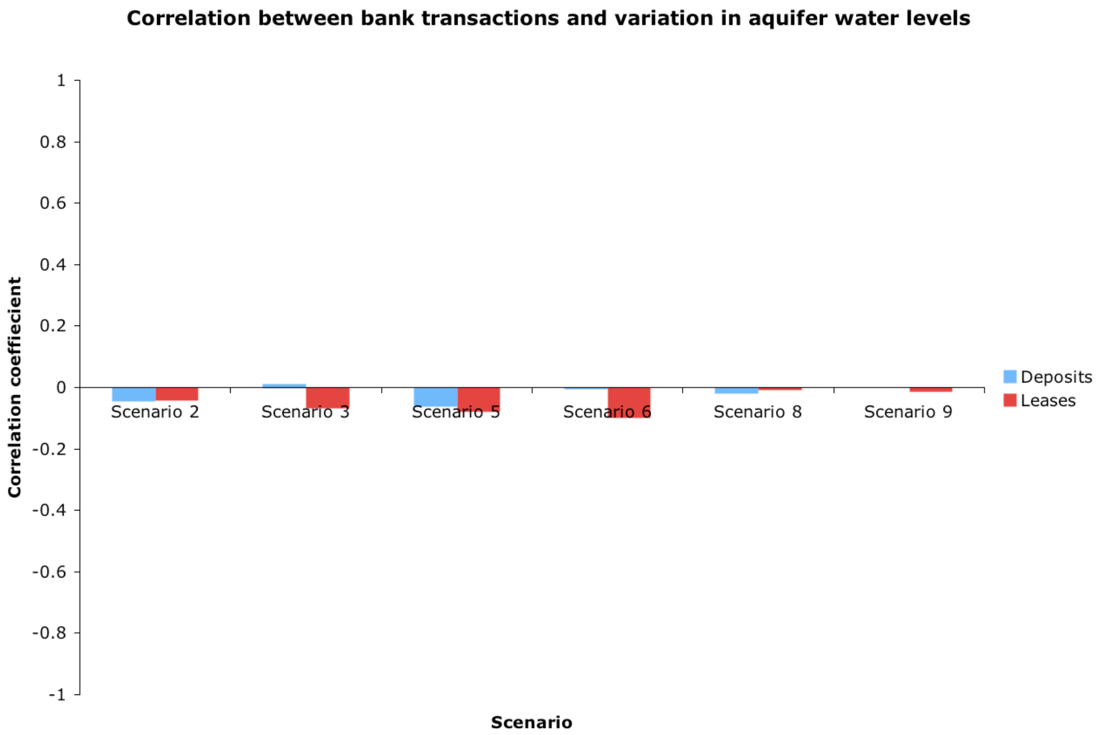


Figure 68: correlation coefficients calculated between bank transaction frequency and aquifer water levels. In all scenarios, there is little evidence of a strong relationship.

However, we can explore the ranking of scenarios by deposit volume, to see if the higher deposit volume scenarios tend to be the more sustainable scenarios (Table 2, below). With the notable exception of Scenario 2, the top three sustainable scenarios are those that saw the highest deposit volumes. The relationship appears to be less clear for lease volumes: the top two lease volumes were experienced by sustainable scenarios, but the third top lease volume is in an unsustainable scenario. From these two tables it might be reasonable to say that deposits have a stronger influence on the aquifer water level than leases.

Table 2: scenarios ranked by deposit volume (first = highest volume) and sustainability from the perspective of not experiencing a decline in aquifer level

Scenario	Deposit Volume Rank	Sustainability
6	1	Sustainable
3	2	Sustainable
5	3	Sustainable
8	4	Unsustainable
9	5	Unsustainable

Scenario	Deposit Volume Rank	Sustainability
2	6	Sustainable

Table 3: scenarios ranked by lease volume (first = highest volume) and sustainability from the perspective of not experiencing a decline in aquifer level

Scenario	Lease Volume Rank	Sustainability
3	1	Sustainable
6	2	Sustainable
9	3	Unsustainable
8	4	Unsustainable
5	5	Sustainable
2	6	Sustainable

A further question with regard to the state of the aquifer, is the performance of the aquifer over time in relation to the level of conflict in the system. There is obviously no direct link between a social variable such as conflict and a physical variable such as the aquifer, but there are possible indirect linkages (discussed later), and so exploring at a crude level possible correlations between conflict will help decide whether these linkages are worth examining further.

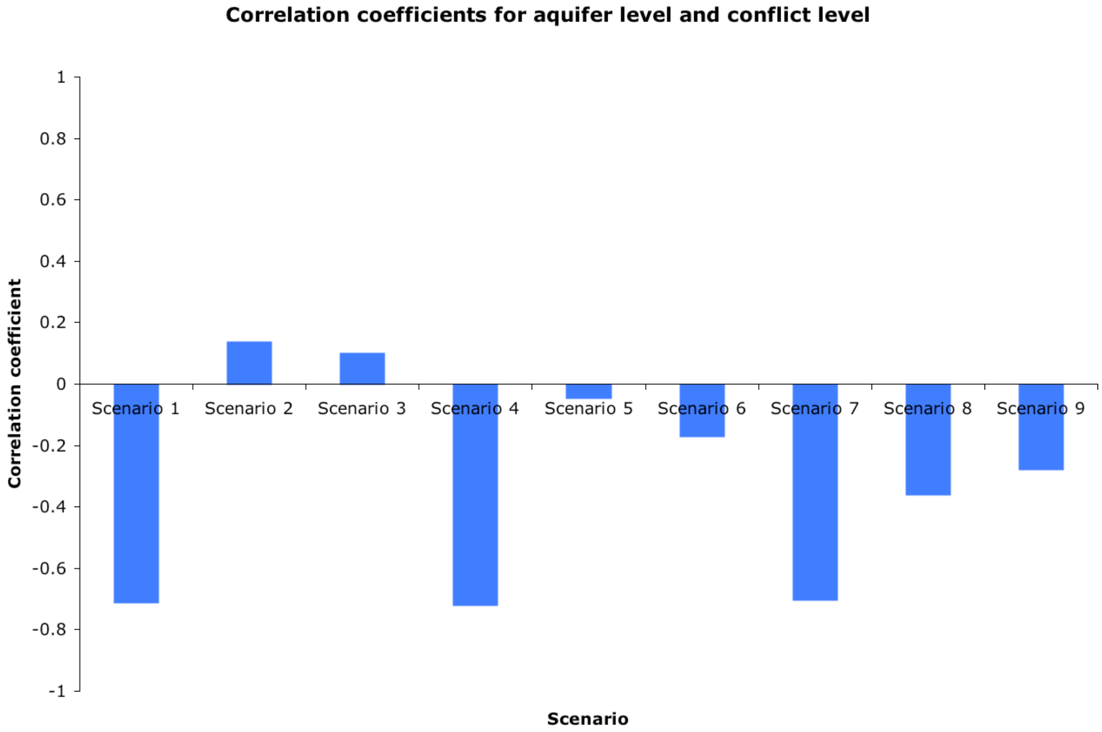


Figure 69: correlation coefficients for aquifer levels and conflict levels

3 out of 9 scenarios show a reasonably strong negative correlation between aquifer level and conflict, such that as aquifer levels go down, conflict goes up. For other scenarios, the correlations are still mostly negative but generally much weaker.

One of the other most significant influences on aquifer state is likely to be the climatic conditions: specifically, amount of precipitation and temperature. Figure 70 below explores correlations between temperature, precipitation and aquifer levels.

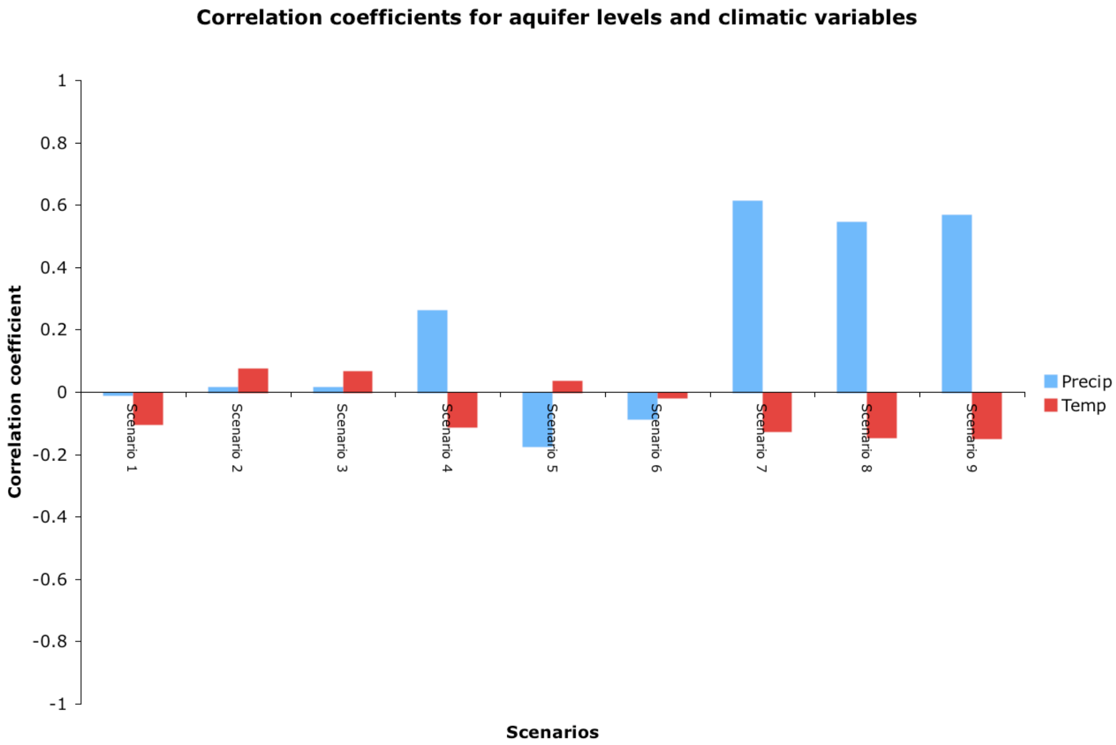


Figure 70: correlation coefficients between aquifer levels, and temperature/precipitation

Scenarios 7, 8 and 9 stand out in an otherwise unremarkable dataset, for having very strong positive correlations between precipitation and aquifer levels, and low negative correlations between temperature and aquifer levels. These scenarios all include the highest degrees of climatic change. Scenarios 1 through 3 show mixed and counterintuitive relations between temperature/precipitation and aquifer levels. Scenarios 5 and 6 show stronger but still counterintuitive relations.

5.2.2.3 ... Results Summary 2-C: state of the aquifer over time

In summary, then, our exploration of the aquifer level data, along with select comparisons, has uncovered the following results:

1. Sustainable scenarios, where aquifer levels increase, include 2, 3, 5 and 6. Unsustainable scenarios, where aquifer levels decrease, include 1, 4, 7, 8 and 9.
2. All scenarios show an initial sharp decrease in aquifer levels, but then diverge.
3. Rates of decrease and increase over time are steady.
4. No correlation is identified between frequency of bank transactions and aquifer levels
5. The sustainable scenarios appear to be more strongly associated with higher deposit volumes, whereas the relationship for leases is less clear.
6. Aquifer levels are generally strongly correlated with extremes of precipitation and temperature, and more significantly so with precipitation. The best correlations are found for the scenarios experiencing the most extreme levels of climatic change.

Conflict and agent internal state

Data gathered during the simulation on agent internal state included:

- Economic, hydraulic and social stress
- Fear of government action
- Risk aversion
- Sociability
- Trust in government/fear of government
- Perception of water availability

The stress variables are ‘catch-all’ variables intended to communicate a broad ‘state of mind’ for the agent: for example, changes in the agent’s environment that lead to the agent having less water may raise the hydraulic stress level of the agent. Similarly, if the prices the agent gets at the end of a year for its harvested crops, the agent’s economic stress level may rise. Note the ‘may’: there are significant stochastic components inside the translation of external stimulus into internal state, and each model replication within each scenario ran with a different random seed. There is no guarantee that an adverse external circumstance will increase the relevant stress variable in any one run. Over time, however, one would expect there to emerge a general relation of this sort.

The varying levels of institutional change incorporate varying levels of government action. Consequently, the agents’ perceptions of the government are important determinants of the state of other internal variables, and their reaction to government action. Both fear and trust in government are captured; these are set at moderate levels to begin with (but including some inter-agent variation set stochastically). Fear usually has the effect of prompting the agent to take action to minimize the risk of a negative consequence. Trust usually has the effect of making the agent more comfortable with a government institution or action. But again, in any one simulation run it is impossible to predict what exactly an agent will do regarding a government action/institution, and given its fear and trust variables.

The ‘social capital’ variable is largely concerned with inter-agent communication and cooperation. Social capital is a dimensionless quantity that is diminished whenever an agent communicates and/or cooperates, and increases when an agent is not communicating or cooperating. The agent’s social capital can potentially have a significant controlling influence on how much the agent communicates and cooperates with other agents. Unfortunately, a problem was encountered in collecting data on the average agent state of the social capital variable, and so I am forced to turn to a different measure: sociability. Sociability is similar to social capital in that it is also affected (albeit) weakly by communication and/or cooperation, but is only used explicitly to help control the spread of rumors within the agent population. Occasionally, an agent will spread a story about some pending governmental action, or some change in the state of some environmental variable (such as that year’s precipitation). The sociability of other agents will determine how far that rumor gets: if the rumor leaves a sociable agent only to arrive at a highly unsocial agent, the rumor will be passed on to far fewer agents than if it had landed at a highly social agent.

Finally, the agents perceive the availability of water for their own use. This is not a direct measure of the actual availability, but is a rough guesstimate each agent maintains as to whether there is or is not enough water in the system for their uses. It is, predictably, affected by the agent's experience over time: if the agent pumps from deeper this year than it did last year, its perception of water availability will go down.

The algorithmic relations between internal variables, and between environmental and internal variables, are fundamentally entirely the creation of the modeler and so - in theory - a simulation should reveal nothing new about a system that the modeler does not already know. However, the combinations of a number of different internal variables acting in concert over different time scales and at different times, are most definitely not pre-established by the modeler (at least, not intentionally). Consequently, it is well worth exploring the relations between internal variables and some of the model outcomes of interest, as well as some of the possible interdependencies within the set of internal variables.

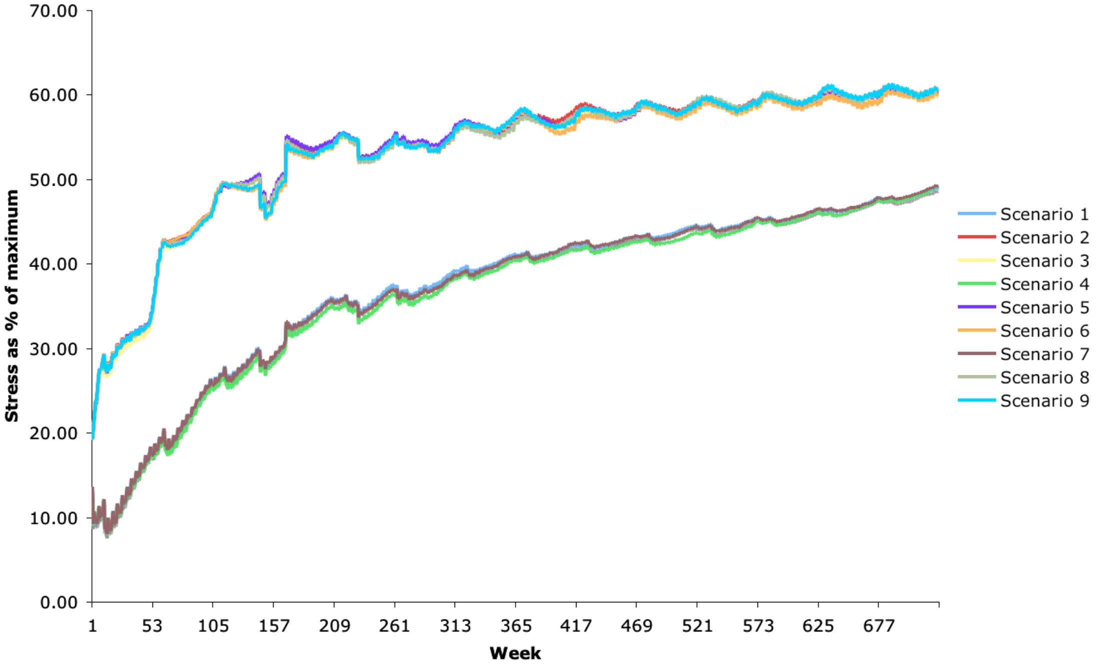


Figure 71: changes in average total stress per Farmer agent; stress plotted as a percentage of maximum stress (all stress variables have minimum and maximum values of 0.0 and 1.0)

Figure 71 above shows two distinct groupings of stress trace: scenarios 2, 3, 5, 6, 8 and 9 see on average 30% higher levels of stress per agent than scenarios 1, 4 and 7. If there are any relations at all between the degree of change in each scenario and these results, it is likely to be with institutional change: scenarios 4 and 7 experience moderate and high physical change respectively, but all undergo low levels of institutional change, perhaps suggesting some sort of correlation with the absence of any institutional change in the system. Another important feature of the graphic to note is that stress increases over time, at first at a fast rate (roughly 10 percentage points per year), and then at a slower rate, for both groups. There also appears to be some annual cyclicity in the pattern of stress: roughly once a year stress experiences a slight drop, before resuming its upwards climb.

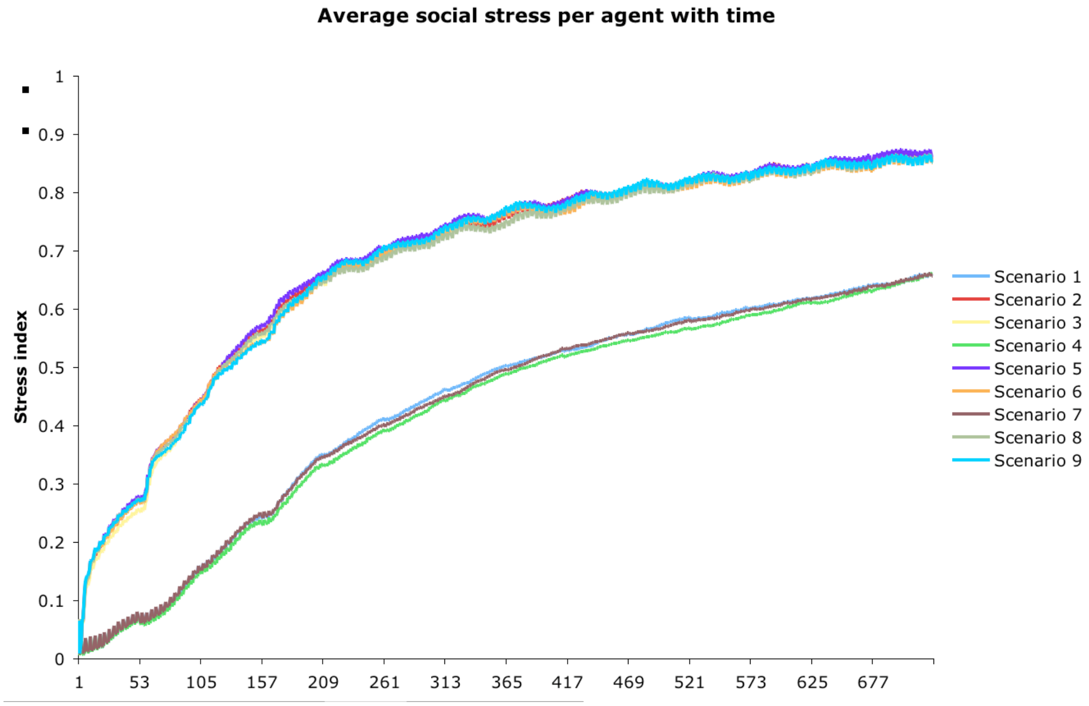


Figure 72: average social stress per agent with time

Figure 72 for social stress shows a similar grouping: scenarios 4, 7 and 9 in the lower stress grouping, and the same annual pattern of variation but confined to the higher stress scenarios. An interesting feature of both this graphic and the previous is that within scenario groupings, the scenarios are exceptionally closely clustered together - within tenths of an index point.

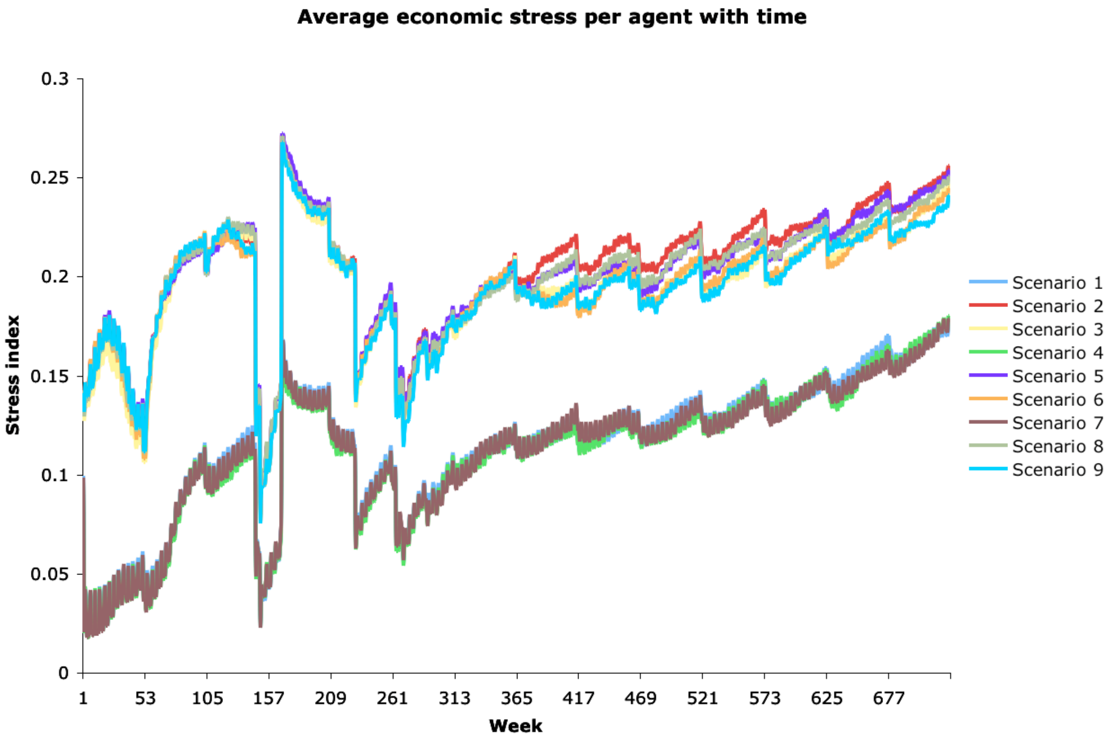


Figure 73: average, per-agent economic stress with time

Figure 73 shows a very different picture compared with social and hydraulic stress. Much higher variability, less of a difference between the two groupings of scenarios, and very strongly pronounced cyclicity on an annual basis in both groupings. Importantly, the first three years are characterized by dramatic variation in stress in all scenarios. Stress does increase throughout the simulation, on average, but actually peaks in those first three years.

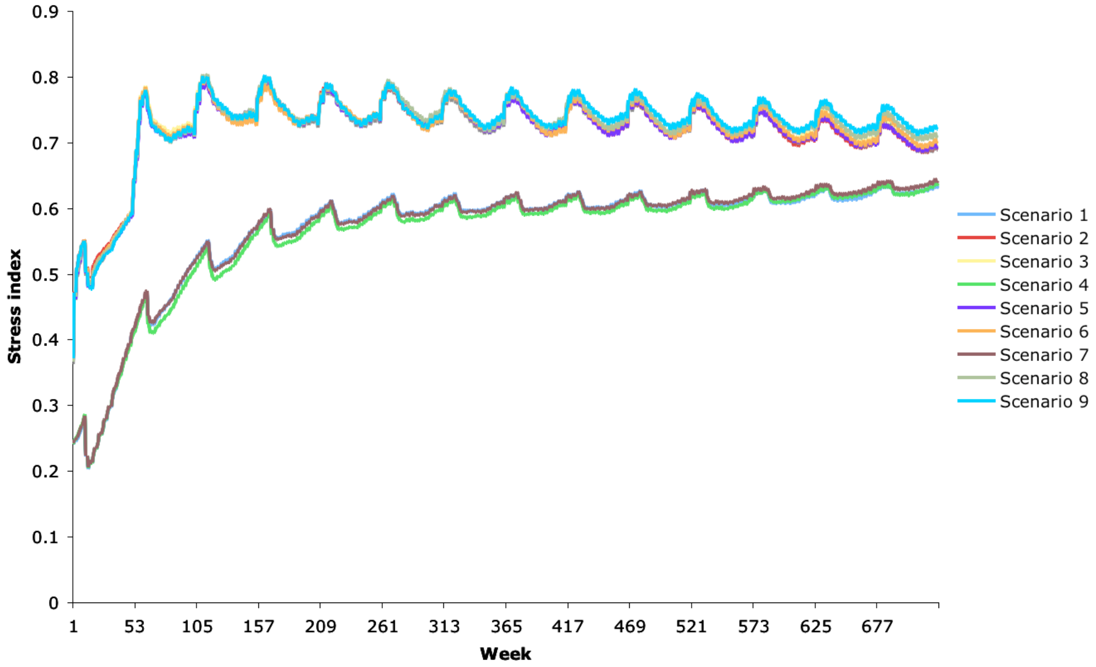


Figure 74: average per-agent hydraulic stress with time

Figure 74 shows the only stress traces that actually decrease in severity over time. The groupings remain the same, but the more severely stressed scenarios show a slow but steady decrease from an early peak. The same annual pattern is visible, and very pronounced in the more severely stressed scenarios. The dramatic increase in stress appears to come at the beginning of each year, followed by a slower decrease in stress towards the end of the year.

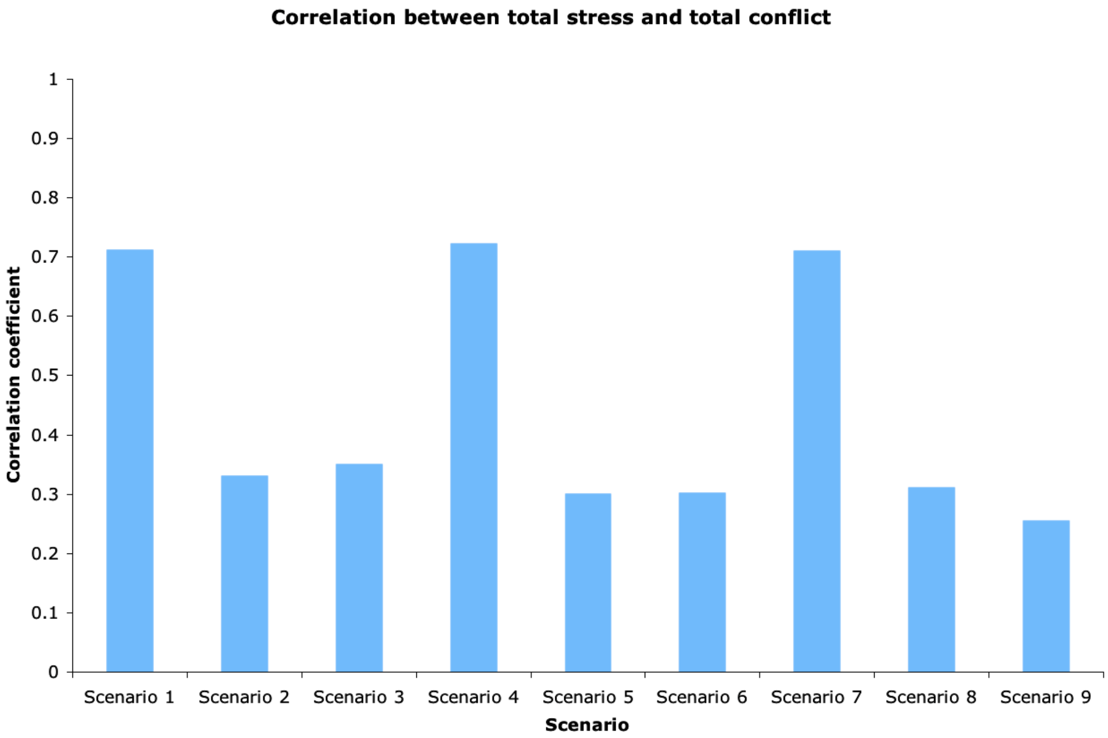


Figure 75: correlation between total stress and total conflict

Figure 75 shows two general groupings: Scenarios 1, 4 and 7 standing out with strong correlation between stress and conflict, and the remainder with weaker correlations. This bimodal distribution suggests some additional control on the stress and conflict; unfortunately, since Scenarios 1, 4 and 7 neatly straddle the entire range of physical change, and all are in the zero institutional change category, attributing the strong correlations between stress and conflict to some element of background change is less easy. This is unless, as suggested earlier, it is the absence of institutional change which is the important factor.

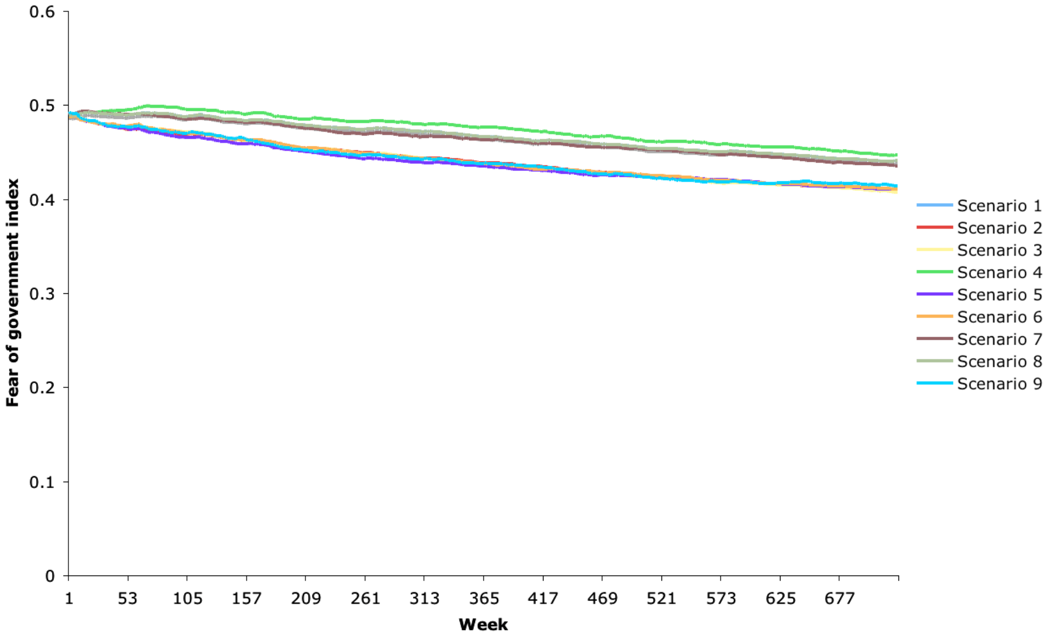


Figure 76: average agent fear of government

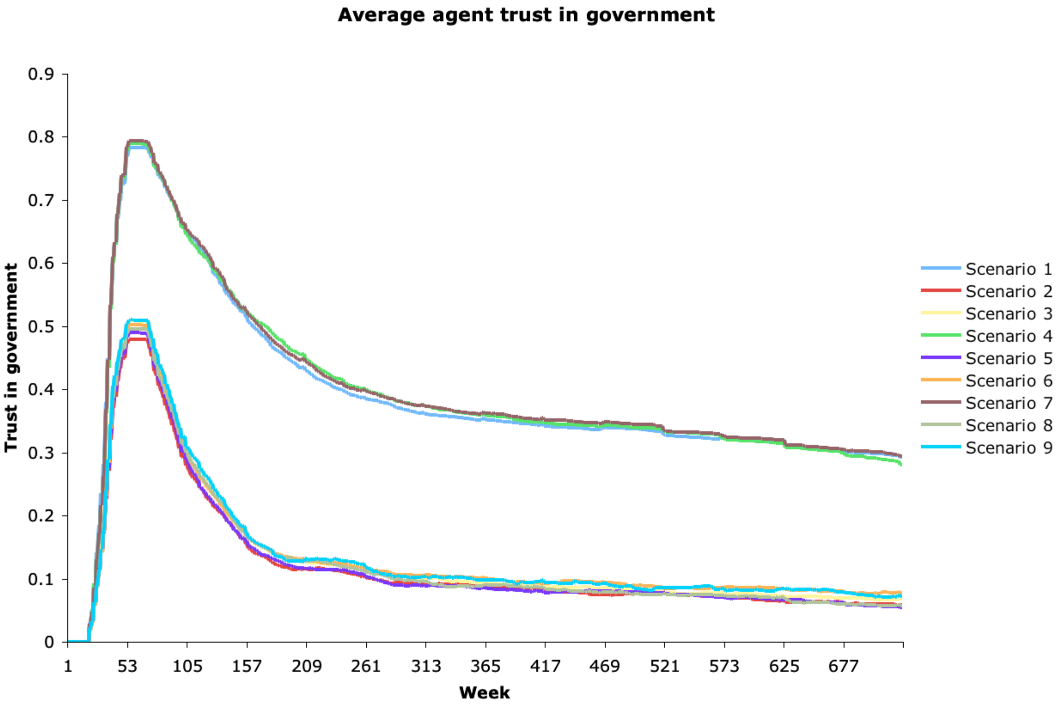


Figure 77: average agent trust in government over time

Fear of government varies little between scenarios, and shows a steady decrease over time. Trust in government, on the other hand, shows a significant peak within the first two years of the simulation, a significant decrease in the next 4 or 5 years, followed by a less steep and more steady decrease to the end of the simulation. Both fear of government and trust in government are, at least in theory, likely to have effects on an agent's willingness and enthusiasm for participation in the ground water bank. Unfortunately, the unusually stable trend for the fear of government variable suggests some artifact of coding or otherwise incorrectly specified feedbacks. Note that in both cases, we see the same scenario groupings: scenarios 1, 4 and 7 together separated from the other scenarios. This grouping experiences higher trust and higher fear than the other scenarios.

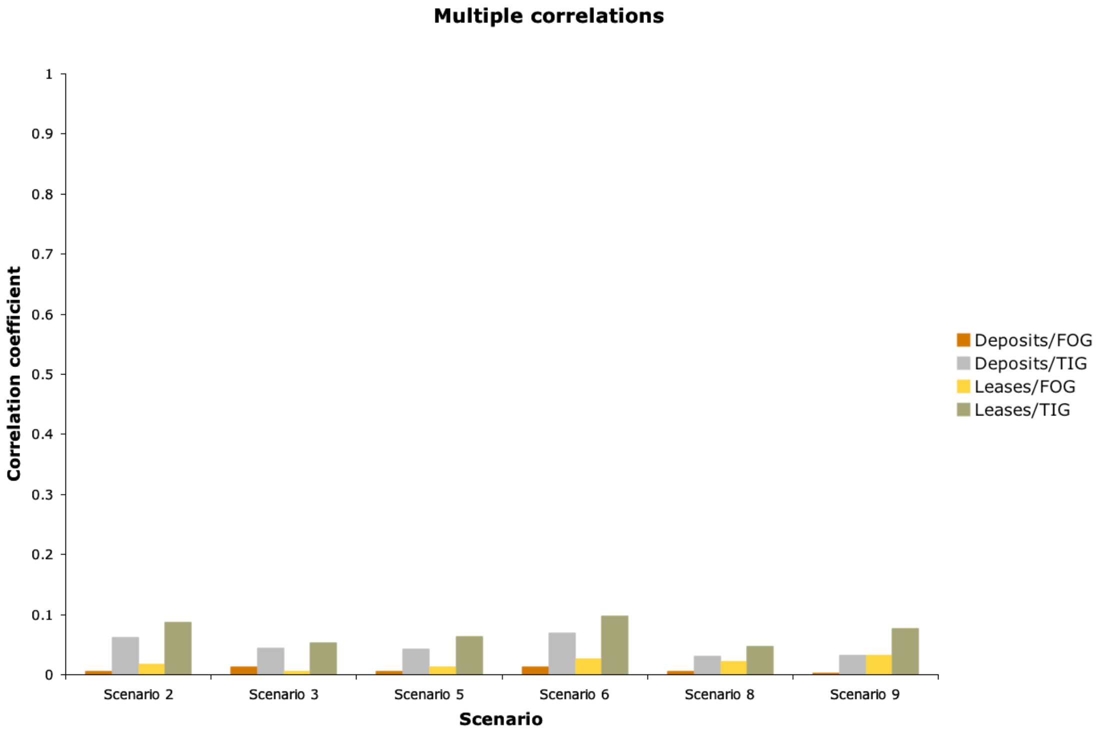


Figure 78: correlation coefficients between deposits and leases in the ground water bank

If we plot correlation data between ground water bank activity and fear of government/trust in government (Figure 78), we see no particularly strong relationship, although leases and trust in government are most strongly correlated.

Finally, we address the relations between sociability and conflict. This is mostly to explore what effect this variable, which is a relatively minor cognitive variable in terms of the number of algorithms is implicated in and by, have on the overall level of conflict and stress in the system. Note that social capital is a similar variable, but data collection problems meant that this dataset could not be analyzed.

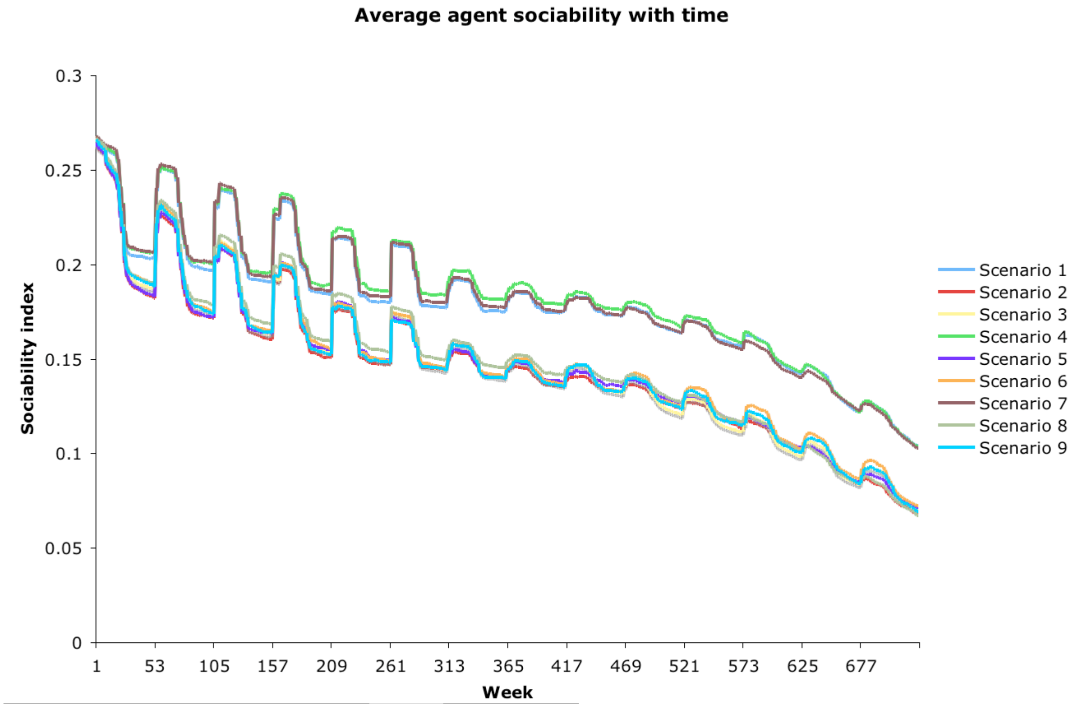


Figure 79: average agent sociability with time

The annual variation we have seen in other variables is present in Figure 79, particularly evident from the start of the simulation through to around 4.5 years. Overall, we see a general negative trend, with the rate of decrease increasing over time. Initial variation in average sociability is high, but the curves appear to settle down with time. Interestingly, we see the same grouping of scenarios here as in earlier graphics: Scenarios 1, 4 and 7 distinctly and separately defined. These scenarios experience higher average sociability than the other scenarios.

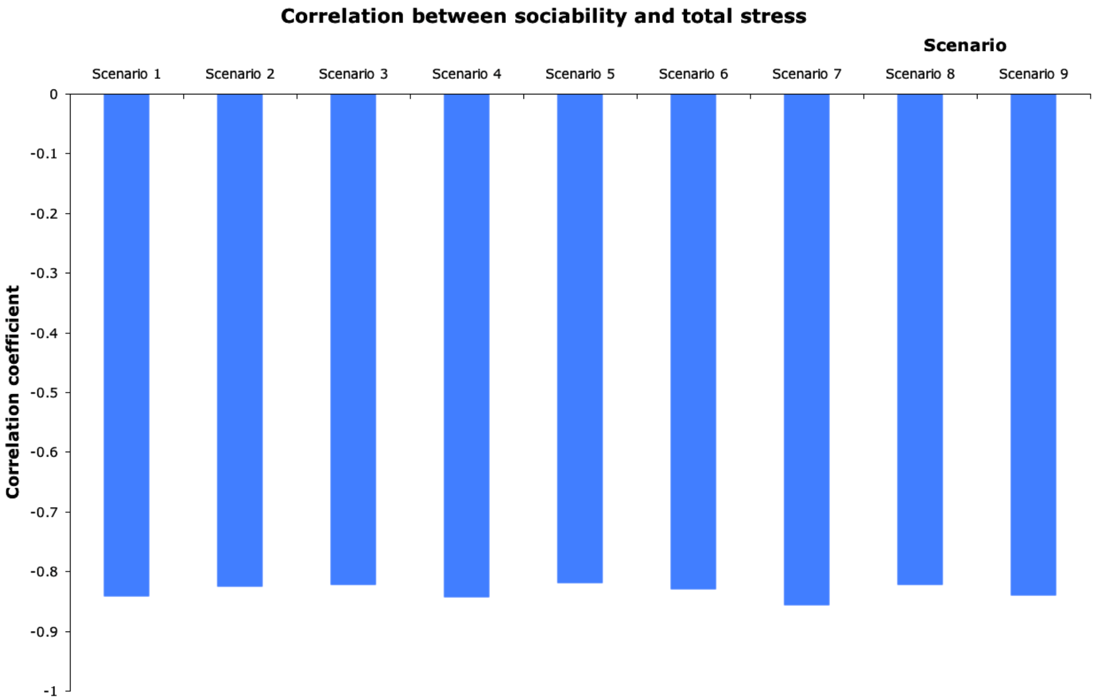


Figure 80: correlation between sociability and total stress

With one of the strongest set of correlations across all scenarios found for any correlation pairing so far, it appears that there is at least some relationship between sociability and total stress, such that as sociability increases, total stress decreases.

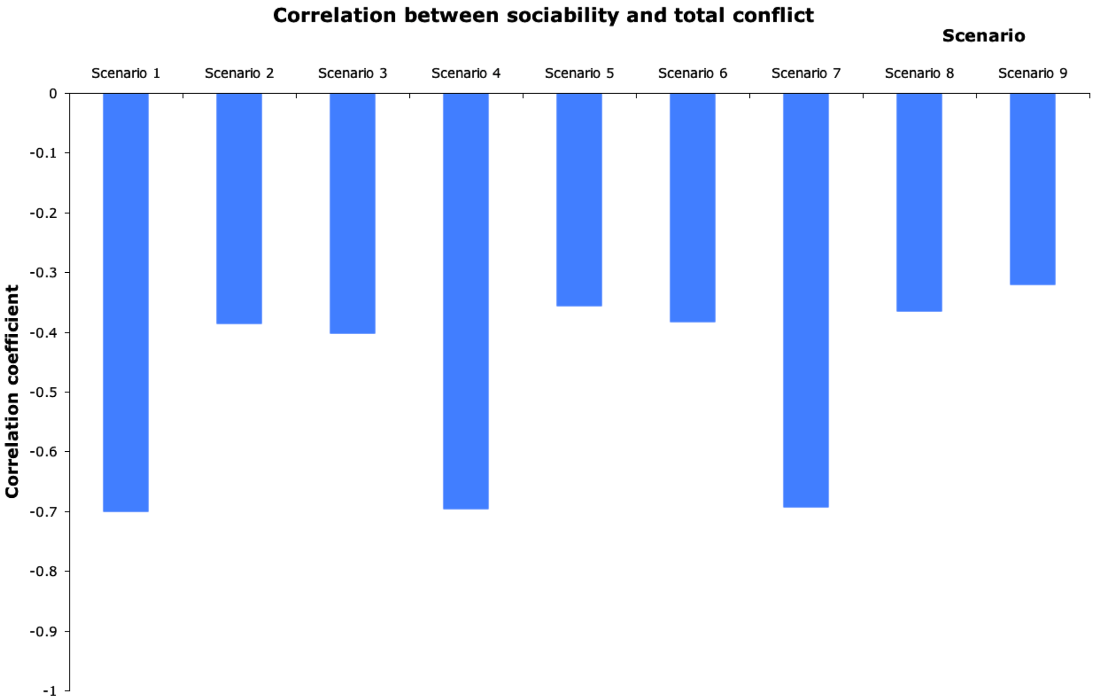


Figure 81: correlation between sociability and total conflict

The correlation data in Figure 81 shows a slightly weaker, but nevertheless impressive set of relationships between sociability and total conflict, suggesting that as sociability increases, total conflict decreases. We also see the grouping of Scenarios 1, 4 and 7 standing out once more.

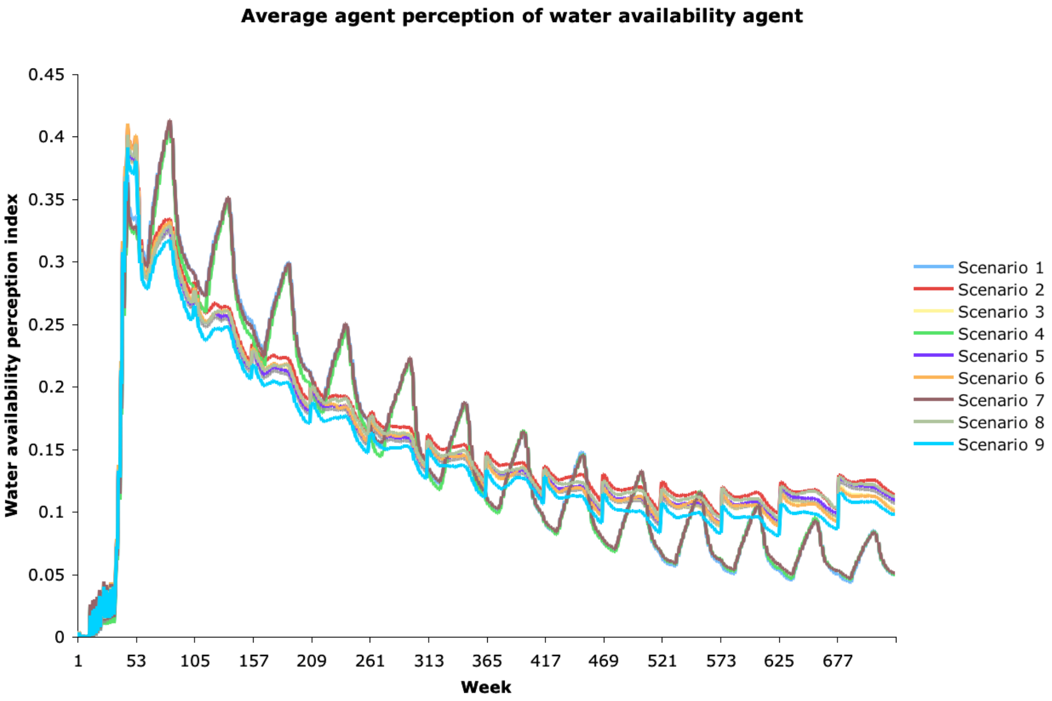


Figure 82: average agent perception of water availability over time, by scenario

This figure is interesting for the way in which the grouping in scenarios we have seen throughout the analysis reappears, but in a different form: instead of being distinctively separate from the other scenarios, Scenarios 1, 4 and 7 follow roughly the same average trace, but experience much greater intra-annual fluctuations. A further important feature of the graphic is the difference in curve trend between banking and non-banking scenarios: Scenarios 1, 4 and 7 show a steady decrease over time, whereas the remaining scenarios show a similar decrease up until around year 10, after which most scenarios show evidence of a slow increase in perception of availability. Finally, note the sharp increase in perception of water availability in the first year, for all scenarios. This may be due to the issue of model equilibration: see the brief treatment of this issue at the beginning of the results discussion.

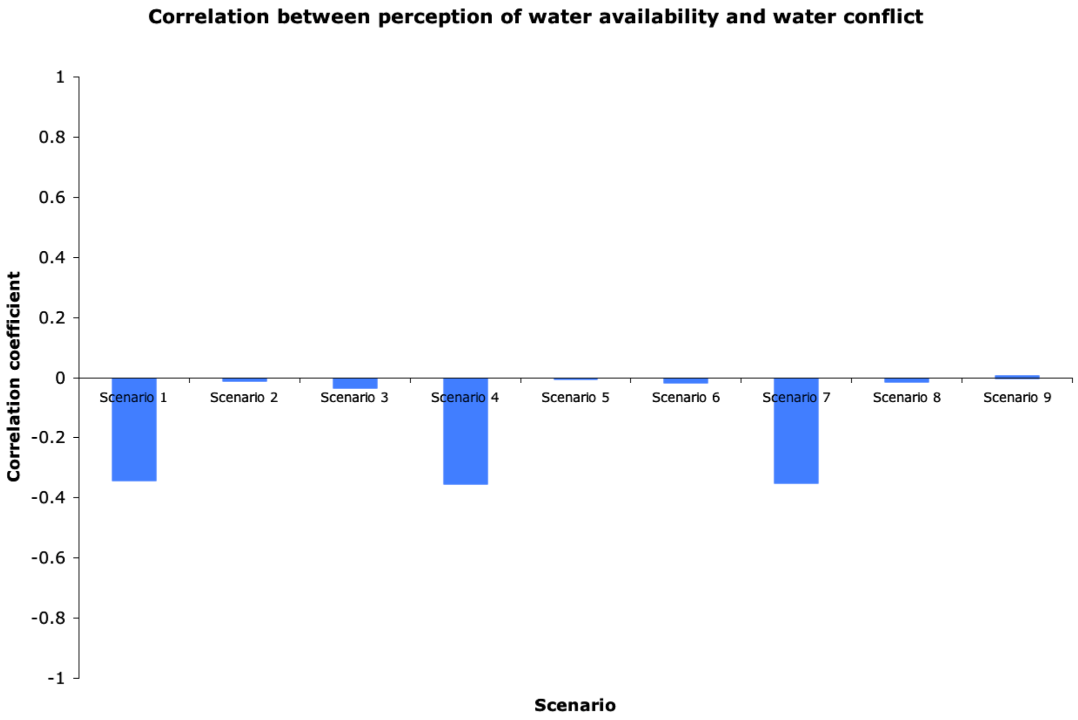


Figure 83: correlation coefficients for perception of water availability and water conflict

Correlations in Figure 83 above are mostly weak, but it is interesting that little or no correlation exists for all scenarios except 1, 4 and 7 - the only scenarios without ground water banking. In other words, for scenarios without ground water banking, the lower the perception of water availability, the higher the level of water conflict (and vice versa).

Finally, I shall briefly explore relations between the key financial states of each agent - capital, debt - and conflict.

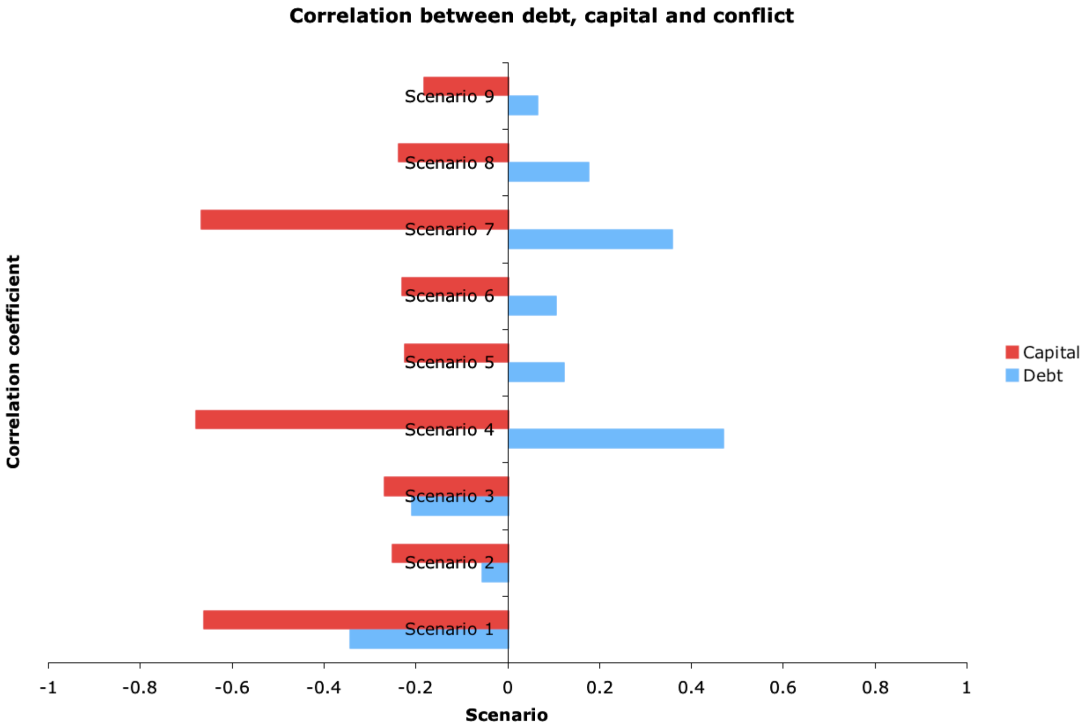


Figure 84: correlation coefficients for comparisons between capital, debt and total conflict

The results are somewhat mixed. Strong negative correlations exist between levels of capital and conflict, mostly in Scenarios 1, 4 and 7: as capital decreases, conflict increases. The same is not true for debt: weaker negative correlations for Scenarios 4 and above, but weak positive correlations for Scenarios 3 and below. This suggests that for scenarios with no climate change, a reduction in debt may be associated with an increase in conflict particularly if no institutional change is encountered. For scenarios with some degree of climate change and across all degrees of institutional change, an increase in debt is correlated with an increase in conflict.

5.2.2.4 ... Results Summary 2-D: conflict and internal agent state

In summary then, our analysis of cognitive variables has turned up the following features of the data:

1. Average stress increases over time for all scenarios.
2. Scenarios are grouped by stress: Scenarios 1, 4 and 7 with distinctly lower stress on average than the other scenarios.
3. Average stress has distinct but uneven annual cyclicity (increases and decreases).
4. Average stress increases at a faster rate to begin with than towards the end of the simulation.
5. Social stress shows the same groupings as for average stress, with a faster rate of increase at the beginning of the simulation.

6. Economic stress shows significant variation among all scenarios at the beginning of the simulation.
7. Economic stress shows similar cyclicity and groupings to the other stress types.
8. Hydraulic stress shows similar cyclicity and scenario groupings to other stress types.
9. Hydraulic stress for all scenarios except 1, 4 and 7 decreases over time, with annual variation.
10. Scenarios 1, 4 and 7 show the strongest correlations between conflict and stress, but all scenarios show some evidence of a correlation.
11. Average agent fear of government and trust in government both decrease over time, but trust in government enjoys a brief sharp peak in the first two years of the simulation, followed by a fast then slower rate of decrease.
12. There is little evidence that fear of government trust in government have any sort of correlation with ground water banking activity.
13. There is strong correlation evidence that as sociability increases, social stress decreases.
14. There is reasonably strong correlation evidence that as sociability increases, conflict decreases, particularly so for Scenarios 1, 4 and 7.
15. For Scenarios 1, 4 and 7, agent perception of water availability decreases steadily throughout the simulation. The other scenarios show a decrease until year 10, and then a slow increase.
16. Intra-annual variability in perception of water availability is much higher for Scenarios 1, 4 and 7 than for the other scenarios.
17. All scenarios experience a dramatic increase in perception of water availability within the first year of the simulation.
18. Water conflict appears to be sensitive to agent perception of water availability only in Scenarios 1, 4 and 7.
19. Capital is strongly negatively correlated with societal conflict, particularly in Scenarios 1, 4 and 7. Debt is more weakly positively correlated with societal conflict across all scenarios

5.3 ... Discussion

As for the Results, in this section I will address the results of GWBSIM and AlbAgent simulation runs separately, and then comparatively. The fourth and final section of the discussion will be discussing data relevant to the sub hypothesis - the concept of the universal hydrologic agent. The intent of the discussion is to make and justify a series of statements as to whether the hypotheses can be supported, denied, or remain indeterminate. Note that, in the following discussions, I will indulge in some degree of agent anthropomorphism: agents will 'know', 'react', 'feel' and 'act'. In reality, despite the more than 50,000 lines of code in GWBSIM, the agents get nowhere near knowing, reacting, feeling and acting in any sense approximating the real world. However, agents do 'know' due to hard coded variables, received messages, and stored memory; agents also 'react' through hard coded and dynamic feedbacks; agents 'feel' changes through direct observation of the system and messages from fellow agents; finally, agents 'act' by activating pre-specified methods for action. Where I slip into the convenient vocabulary of personification, it is not intended to attribute or otherwise apply any deeper intelligence to the agents than is already provided by existing cognitive mechanisms specified in the model..

5.3.1 ... A note on achieving steady state

A number of the datasets reviewed so far have shown interesting behavior along the following lines: anomalously fast rates of increase/decrease, or anomalously high/low levels of variability from 0% to <30% of simulation time. Soon thereafter, the datasets settle into more consistent trends or cycles. At times in the following discussion, explanations may be offered for this 'settling down' period, but there remains the general possibility that the models are in fact just proceeding to an equilibrium state (or set of behaviors). Lerman (2000) conducts mathematical analyses of coalition-forming agents, showing that different initial parameterizations led to marked changes in the amount of time her system would take to reach a steady state. In effect, the time taken represents the gap between the actual initial values of the parameters, and what values the normal operation of the model will end up setting the parameters at. The two are rarely close together, particularly for complex models where the modeler may have little or no idea of the final sets of interactions affecting any given parameter. The further apart the two values, the longer the model will take to achieve that equilibrium state - or the steeper the rate of change from initial values to equilibrium values. It is possible that the trends seen in several datasets may have some explanation along these lines. However, it does not preclude other explanations: while the model is achieving steady state, all its normal mechanisms are operating, and so variation within that progression period may well be attributable to some other causal relation.

5.3.2 ... GWBSIM discussion

5.3.2.1 ... Summary 1-A

1. The -GWB scenario showed overall higher levels of conflict frequency and severity across all years of the simulation, in terms of both complaints and court actions.
2. The level of court action-related conflict severity was low for -GWB, but still significantly higher than for the +GWB scenario.
3. The +GWB scenario showed low levels of conflict frequency and severity in general, with no court actions encountered at all in any year.
4. The +GWB scenario matched the -GWB in terms of complaints for the first couple of years of the simulation, but thereafter showed a significant decrease in conflict severity and frequency. The -GWB scenario showed a steady increase in complaint frequency and severity over time, but a relatively stable level of court action frequency and severity over time.

The major hypothesis suggested that the major institutional perturbation of a ground water bank, in an institutionally ‘frozen’ system, would cause a reduction in conflict frequency and severity. These results appear to provide strong support for this hypothesis. Both scenarios were run over the same periods, with the same parameterizations from the same Latin Hypercube sample. The only significant macro-structural variation in the two artificial societies was the introduction of the ground water bank, and so it is reasonable to say that the ground water bank as an institution had a strong negative effect on the frequency of conflict and the severity of conflict in the artificial society. The ground water bank scenario still experienced conflict, in the form of complaints. Complaint generation, however, is a much less severe expression of agent problems than court actions. Court actions require capital expenditure, handicaps on agent action, negative changes in emotions, and often extensive cooperation with other agents (i.e. repeated exchange of messages related to the court action event). Consequently, a high complaint generation frequency on its own is no match for even a low frequency of court action generation or court action-related conflict severity.

The fourth finding in Summary 1-A suggests some important points: first, the initial increase but then steady reduction in complaints for +GWB over time could be linked to the non-availability of ground water banking for the first year of the simulation. Under the ground water bank’s rules, no withdrawal is allowed on credit, i.e. water has to be present in a reach of the bank from which a withdrawal is requested for that withdrawal has to be approved. Moreover, *enough* water has to be in the bank for that withdrawal not to cause the reach balance to go negative. Consequently, an additional rule was added to the bank that restricted transactions to deposits-only during the first year of the bank’s operation. Given the earlier statement linking ground water banking to reduced conflict frequency and severity, it is also reasonable to suggest that a handicapped version of the bank (i.e. no lease option) would have less of a negative effect on court action and complaint generation. This provides further evidence of the utility of a ground water bank in expanding institutional capacity and lessening the frequency and severity of resultant conflict.

For the -GWB scenario, complaints per year increased steadily over time, while court actions did not. This trend may simply reflect a lack of negative feedback: complaints cost little and achieve little, but do serve to vent some of the agent's stress (stress levels are allowed to decrease slightly when a complaint is generated by that agent). There is little incentive over time to not keep complaining if things are not going well; as later graphs showed, agent stress continued to rise across all SWI agents in the -GWB scenario. Consequently, over time, more and more agents will have experienced conditions conducive to generating a complaint. The stability of the court action frequency over time is a little more puzzling: why did these remain stable while more agents became more stressed over time? A possible answer is in the type of agent most stressed in both scenarios: SWI. These agents have less resource certainty than GWIs (they are more subject to fickle variations in climate than ground water agents) and fewer resources to begin with (SWIs begin with less capital than GWIs). Figure 85 below shows the average per-agent court action frequency for the -GWB scenario:

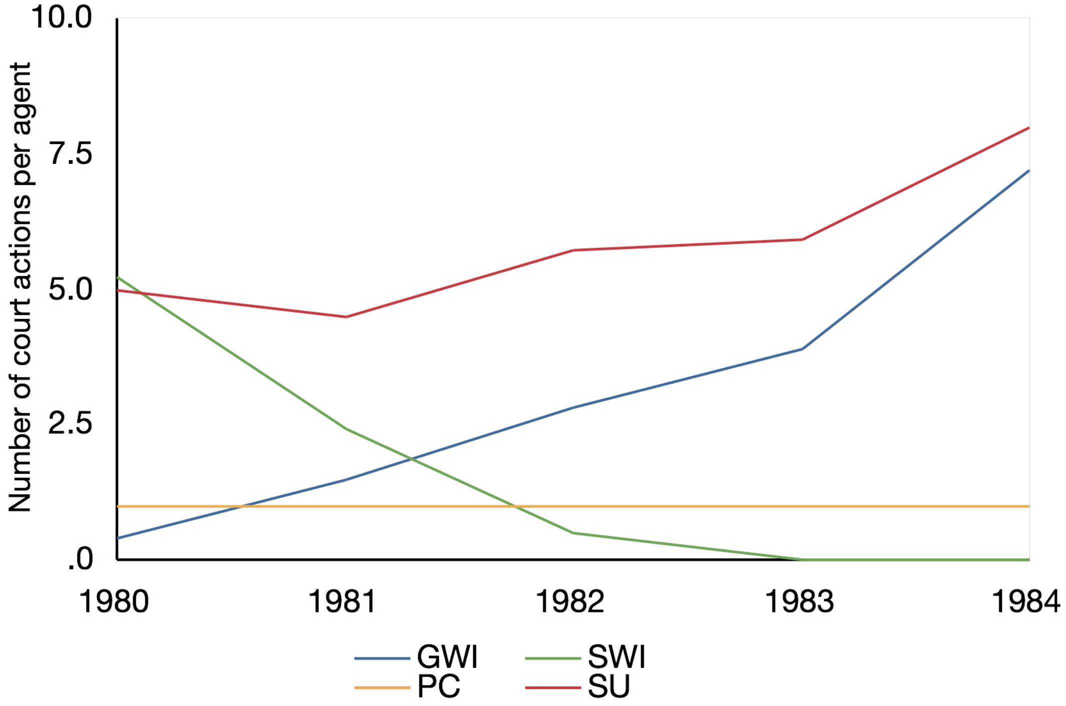


Figure 85: per-agent court actions by year, -GWB scenario.

We see that court action frequency for these vulnerable SWI agents decreased over time - but as we know, their stress did not. The most likely explanation is that they simply ran out of money and/or social capital: court actions require expenditure on the part of each participating agent, and so they may simply not have had enough financial resources to justify another court action. These actions also require expenditure of 'social capital', a resource designed to limit the amount of communication and cooperation agents can engage in (and reflect real world logistical and physical limits on the same), and so social capital may also have run out. However, the plot shows SU and GWI agents taking up the slack, filing court actions as the SWI agents reduce their generation frequency. This goes some way to explaining the relatively stable level of court actions over time: an initial high level as SWI agents responded to adverse conditions, then remaining stable as the contribution from SWI agents decreased and the contribution of other agents increased.

5.3.2.2 ... Summary 1-B

1. GWI agents dominated both leases and withdrawals from the bank. Note that only GWI and SWI agents were allowed to participate in the bank.
2. GWI deposits were a far more significant contribution to the bank than leases. This was reflected in the overall upward trend in the bank's balance over time.
3. Deposits increased in volume over time, and the per-agent deposit volume also increased. Leases showed no such trend, peaking in mid-simulation but decreasing to near zero by the end.

The dominance of GWIs in ground water bank transactions is most likely related to the fact that SWI agents could not physically undertake leases (being without the pumping infrastructure to abstract the water from the aquifer). This was the simplest conceptualization of the ground water bank: in a more elaborate vision, SWIs could lease water by buying credits from the bank and then giving them to local GWIs, in return for those pump-equipped agents abstracting water from the aquifer and adding it to the local canal. Since SWIs could not lease, they did not have the same motivations for participation. GWIs could deposit in the knowledge that the more deposits they made in good years, the more they would have to call on through leases in bad years. SWIs could only hope for some monetary gain by depositing excess or otherwise unwanted water, and no hydrologic gain in drought years. In the absence of the environmental data, it is not known whether simple below-average conditions led to little excess water for SWIs to contribute to the bank.

The significantly higher volume of deposit volumes versus lease volumes has a number of possible explanations. Initial disparity can be explained by the simple fact that leases were not permitted for the first year. Later disparity is more ambiguous in origin: if GWIs have excess water under their water right every year, they are likely to continue contributing to the bank every year, and possibly more as years go by. All bank-participating agents had an internal measure of 'model trust'. This variable corresponded to the level of trust the agent had in the SME-run model by which the bank was administered (i.e. the gamma response functions; see earlier discussion). Simple positive feedbacks would increase model trust if the agent participated in the bank and received no resultant harm (and vice versa). Higher trust in the bank's administration increases the likelihood that the agent will participate in the next run, so creating a feedback loop ensuring repeat participation for some agents. Note that runaway feedback loops are unlikely, partly because these were rigorously controlled for during design, and partly because all cognitive variables have some stochastic variability introduced each time step that should lessen the likelihood of runaway feedbacks developing.

Deposits are a relatively safe, guaranteed source of income if the agent has excess water. If the agent is making a deposit at some opportunity cost for another use (e.g. to grow crops), in the belief that returns will be higher off the deposit than the alternative use, the risk is higher. GWIs are more likely, with their more secure water supply, to make deposits with excess water. SWIs are far less likely (as was shown) to take that risk, since they have a more fickle supply and are likely to develop a higher risk aversion due to more variable water supply and a lower capital base. Consequently, while GWIs will keep making deposits, and their model trust will steadily increase as a result, SWIs are more likely to remain below the 'trust bar' for participation - both deposits and leases. Moreover, GWIs may not need leases unless they are under mitigation orders from the SME, and these are rare (both in the model and real life). The combined result is that safe, beneficial deposits will be made in increasing volume, while leases remain an uncertain quantity and not necessarily undertaken unless macro-scale forces dictate (through mitigation plans). It would take further work and tailored experimental runs to deduce what the real sensitivity of agents is to risk and whether this really affects deposit/leasing behavior.

However, Figure 86 below shows that GWI model trust decreased subtly over time, while SWI trust remained static.

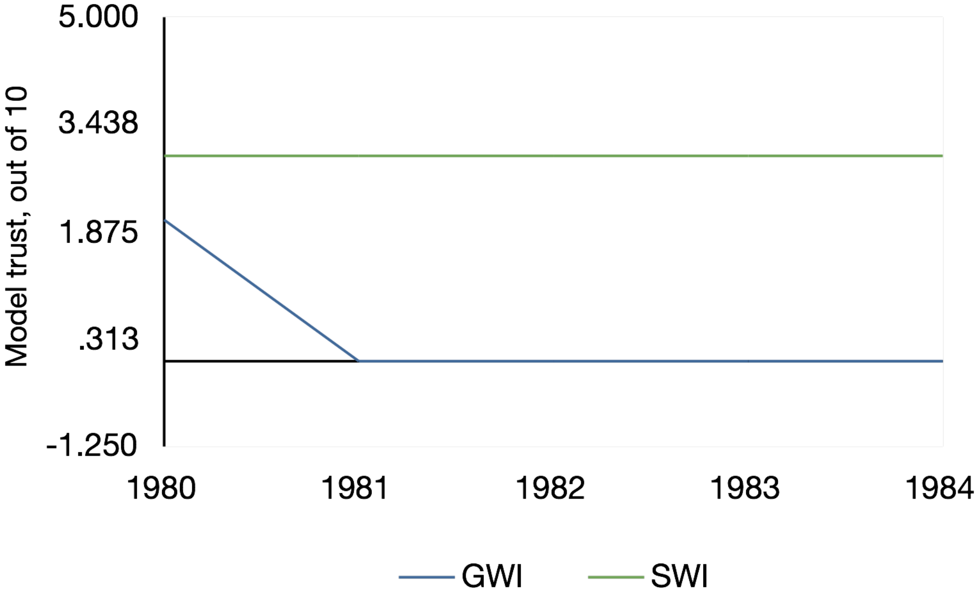


Figure 86: changing trust of ground water bank-participating agents in the bank, over time.

Model trust is clearly not a strong determinant of bank participation, since it decreased or was static over time despite considerable variation in agent deposits/leases. A simple explanation for the lack of strong increase in model trust is the lack of strong payback on the deposit. While each GWI gets a certain trust boost if participating is successful and does not cause harm, the boost is greatest if the agent receives a payback. Since leases were so much less in volume than deposits, only a certain proportion of GWI agents who deposited would ever have received a payback (payment for deposit occurs on a 1:1 basis for the same volume of leases). Without all agents receiving good returns on their investment in the bank, model trust would remain static or decline.

Given this result, we must modify our explanation for increased deposits over time, and the deposit/withdrawal disparity. Instead of model trust having a significant feedback role in promoting future participation, it is most likely, and simplest, to suggest that GWI agents deposited so much more because the risk was low enough to make it worth the effort despite the resultant lack of payback. Deposit of excess water in the bank represented an almost risk-free action for GWI agents (a deposit is simply an act of foregone pumping and so requires no actual physical action on the part of the GWI agent), and so deposits would continue year-on-year despite most of them not gaining financially from the transactions.

This discussion helps us explore why exactly the ground water bank appears to have such a beneficial effect on conflict frequency and severity. It does not appear to affect SWIs much, since these do not participate in great numbers in the bank. Consequently, we see higher levels of stress from SWIs in both + and - scenarios. We see reduced stress in GWIs partly because they are gaining financially from participation (which has positive feedbacks to stress levels, as shown in the financial data analyses), but also because they are gaining emotionally: bank participation was linked in the emotional engines to reductions in stress and reductions in perceptions of future mitigation. In other words, a GWI would deposit and thereafter believe the SME was less likely to impose restrictions on future water use given the deposit action. The reduced GWI stress appears likely to contribute most or all of the reduced conflict severity in the +GWB scenario. This is most relevant to court actions; GWIs are better off than SWIs, and so more able to launch court actions in the first place. If these agents are less stressed through a ground water bank, then we might expect fewer court actions.

One question remains to be addressed: why the reduction in court actions from SU and PC agents for the +GWB scenario? Neither participates in the bank, and so neither should stand to directly gain from its operation. One possible answer lies in the probable environmental effects: deposits in the bank lead to increased flows in the downstream springs, which spring users depend on, and in the river itself, which the power company depends on. With higher flows due to ground water deposits, overall PC and SU propensity to launch court actions is theoretically likely to be lower. Without the environmental data, the truth in this suggestion is unknown. Another possible answer lies in the power of inter-agent communication. Agents periodically trade belief ‘values’ with each other (e.g. one agent’s trust in the ground water bank is at 4.5, and it communicates that value to another agent, which may increase or decrease its own level of trust accordingly); which beliefs are traded is randomly chosen by the source agent. Agent perception of conflict will have been one such belief traded, and so it may be possible that reduced reductions in GWI stress from bank participation could have been spread among a wider agent population and caused knock-on stress reduction effects. This mechanism was not fully tested prior to being implemented in GWBSIM, and so little is known about the dynamics of message propagation in the agent population.

5.3.2.3 ... Summary 1-C

1. Across all agents and both scenarios, the financial variables appear to have the strongest relationships with conflict frequency. Higher capital equates to fewer complaints and court actions, and higher debt to more complaints and court actions. Higher debt appears to have more of an effect on complaint frequency than court action frequency.
2. Relationships between variation in emotional parameters and conflict frequency are decidedly mixed: for example, some agents appear to have inverse relationships between happiness and conflict frequency, other agents strong positive relationships.
3. Social capital is an important parameter for agents, being positively correlated with complaint frequency for both GWI and SU agents.

It is not unexpected that financial variables have the strongest correlation with conflict frequency. Finances are at the heart of what makes an agent tick: most agents want to make money to pay off debts (no agent is debt-free in the model) and stay in business. Experiencing financial hardship is one of the strongest influences on emotions coded into the model: it is one of the few variables compared frequently with the desired state for that variable. Note the cognitive mechanism in operation here: the original intent was to have the agent periodically check all cognitive variables (where appropriate) for correspondence to desired levels, and change other cognitive variables on the basis of the check. For example, the agent may have desired a value of happiness at 6.0, and finding that current happiness level is 4.0, which could have resulted in an increase in stress levels. However, by the time the runs had to be completed, this mechanism had not been implemented for all cognitive variables.

For example, if an irrigator agent's debt payment one year is a certain percentage higher than the desired level, the agent's income stress, risk aversion and hostility may rise by a moderate amount. It is entirely reasonable, then, to see agents responding to higher capital and lower debt with lower propensity to generate conflict. This is probably one of the main channels of influence of the ground water bank: providing a supplemental source of income that is relatively secure, it will act to reduce agent stress via increasing an agent's capital reserves and helping to reduce debt.

It is also not unexpected that variation in emotional parameters and conflict frequency are difficult to link together in any conclusive manner. The agents have a complex range of emotions affected in a complex range of ways. Emotions are impacted by fuzzy logic modules (particularly happiness), as well as by simple stimulus learning cycles - negative response in particular environmental variables will lead to negative changes in certain emotions. However, in model development care was taken to ensure that no single environmental or internal variable would have a dominating change on emotions. All fuzzy logic modules and feedback cycles have at most moderate (+/- 1.0 emotional units) effects on emotions. The result is a mixed bag: variable strengths and directions of relationship between certain internal and external conditions. There may be broader scale relationships not being identified with such a small sample set, but this remains for further work.

The strong relationship between social capital and complaint frequency is directly linked to a condition in the complaint generation algorithm for all agents: this requires a certain level of social capital before a complaint (or indeed, a court action) can be launched. This was intended to reproduce in a more simple manner the real world concept of a conflict causing some social disturbance: agent stress increases when they perceive a higher level of conflict in the basin as a whole, and the agent instigating a conflict experiences some decline in social capital. Compare this to the real world statement - “he’s always complaining”, which is generally taken to be a negative condition. Survey data gathered in January 2007 revealed a dominant view among stakeholders that particular individuals and organizations had a certain propensity to generate conflict regardless of the actual seriousness of the conditions in the basin. To convey the reduced respect that these stakeholders appeared to have, the ‘social capital tax’ was introduced in the model to require some initial level of social capital before an agent was able to generate a complaint or instigate a court action, and cause a decrement in social capital when a conflict was launched. Figure 87 below shows some interesting trends in a comparison between social capital and court action frequency over time (-GWB scenario). SU, with the highest court action generation frequency of any agent, increasing over time, shows the highest ‘social capital payments’ - social capital decreases steady over time. The picture is the same for GWI: steady increase in conflict generation equates with a steady decrease in social capital. The picture is more mixed for PC and SWI, but these agents were in general less of a source of conflict and so this is not unexpected.

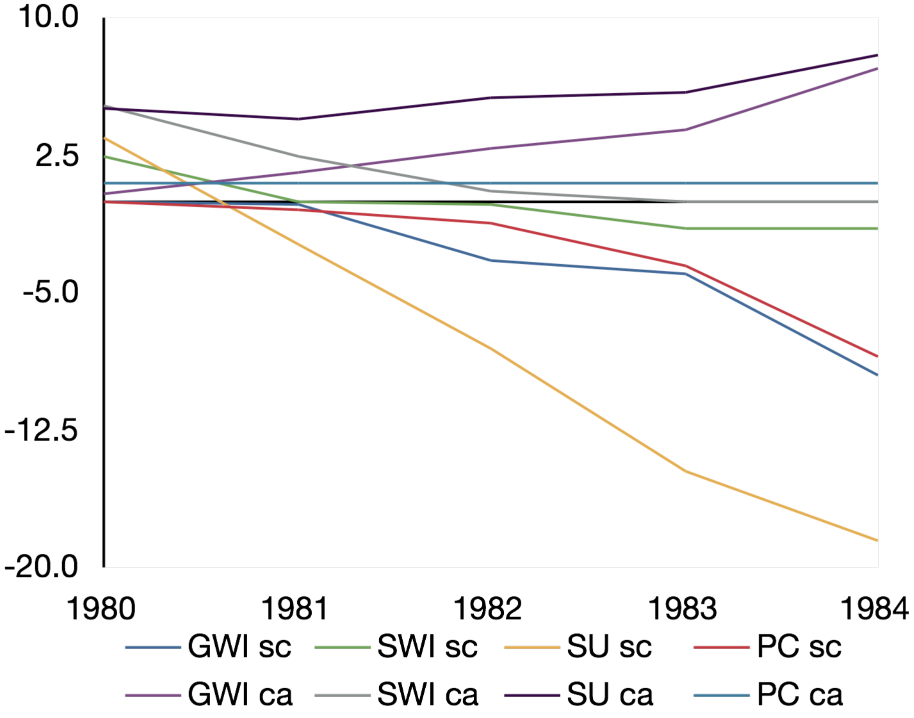


Figure 87: agent sources of court actions, plotted with variation in social capital. Note: ‘sc’ is an abbreviation of ‘social capital’, and ‘ca’ of ‘court action’.

5.3.2.4 ... Summary 1-D

1. Fewer agents go bankrupt in the +GWB scenario compared with the -GWB scenario.
2. Bankruptcy figures for both scenarios are dominated by the SWI agents, and the number of SWI bankruptcies generally increases during the simulation run. This is generally true of all other agents who experience bankruptcies.
3. Court action frequency generally increases over time in the -GWB scenario (remember that no court actions were generated in the +GWB scenario).
4. The SWI and PC agents generate little or no conflict in the +GWB scenario, but constant or declining levels of conflict in the -GWB scenario.
5. The SU and GWI agents are responsible for the bulk of the complaint and court action generation in both scenarios.
6. The -GWB scenario sees the agents in their most stressed state, for both income and water stress.
7. SWI agents experience the most water and income stress out of all agents, in both scenarios.
8. Both water and income stress tend to increase over time for SWI agents, but decrease or remain static for most other agents.

The final summary provides support for some of my earlier propositions. In keeping with the overall strong evidence that the -GWB scenario results in more stress and more conflict for the agents, bankruptcies are higher for the -GWB scenario. This is not unexpected, and nor is the dominance of the bankruptcy figures by the SWI agent type. SWIs, as briefly discussed earlier, are perhaps the most economically vulnerable of all the agents. Whereas GWIs have wells that insulate them from the vagaries of climatic variation, SUs have a reasonably steady income stream from their industrial activities (and only slow response in the springs to reductions in overall system flow), and the PC has an enormous capital base to fall back on relative to other agents. SWIs start with little capital and a lot of debt, and then have to survive fluctuations in market prices, increasing costs and highly uncertain climatic influences on river flow. The increase in per-year bankruptcies over the course of the simulation run is not as easily explained, however: possibly, the income stress of agents is spreading by the simple communication mechanisms available to agents, resulting in a higher likelihood of declaring bankruptcy over time as more and more agents go under. Similar increases in per-year frequency of court actions are also most likely linked to increases in overall system stress (across all agents) with time. This suggests an important phenomena in the artificial society: inertia in the build-up and impacts of agent stress (both water and income-related). Once stress starts to build up, it may be self-propagating. As more agents become stressed for legitimate reasons (adverse changes in internal or external conditions), other agents perceive this stress and become stressed themselves. The validity of this mechanism is not entirely proven, since in the real system it is not known if there is a similar 'runaway bankruptcy/stress/conflict' trend. However, systems do go through tipping points that shift the entire system from one equilibrium to another (some might argue the bull/bear market cycle is just such an example); the fact that the runs completed were shortened from the intended model length leaves open the possibility that the 'inertial conditions' might in fact be one side of more cyclical patterns. The later analysis of AlbAgent will show that such conditions can and do exist.

The lack of contribution of SWI and PC agents to court actions in the +GWB scenario was explored earlier, and possible explanations suggested. The lack of participation of SWIs in generating complaints is more interesting, and not entirely explicable. Low PC generation is expected: there is only one agent, and there is only so much conflict generation one agent can manage in one year. The low complaint generation of SWIs may be tied up in the overall vulnerability of the agent type: less capital, both social and financial, to expend on engaging in conflict. The steady increase in SWI stress over time versus the static or decreasing stress levels for all other agents is a puzzling relationship that has no ready answer. Conflict is generally related to stress levels, yet GWI and SU agents generally have much lower stress yet still generate conflict at a steady rate. The reasons behind this are not clear from the current dataset, and remain to be explored in future work.

The finding that the -GWB scenario results in the most stressed agent conditions once again supports the overall finding that the ground water bank appears to have a strong effect on the conflict levels in the model. As discussed above however, there may be some unwanted critical mass effects developing due to the ability of all agents to respond to the stress of their peers.

5.3.3 ... AlbAgent Discussion

5.3.3.1 ... Summary 2-A

1. All scenarios have annual periodicity in conflict.
2. Most scenarios show an increase in conflict with time.
3. Those scenarios with ground water banking all experienced higher conflict than those scenarios without ground water banking.
4. Scenarios with more severe conflict showed peaks in the first 25-40% of the simulation, whereas the scenarios with the lowest conflict peaked at the end of the simulation.
5. No acute conflict was experienced by any scenario.
6. Increases in institutional change were generally accompanied by significant increases in conflict frequency. Increases in physical change were not accompanied by significant increases or decreases in conflict frequency.
7. Peaks of conflict occur when institutional and physical change are at different degrees.
8. Conflict was experienced by the system even without any sort of change, physical or institutional.

The annual periodicity in conflict is reasonably straightforward to explain: an artifact of the design of the government agent, CHJ, and its responsibilities mean that at the end of each year the ongoing conflict register maintained by the CHJ is automatically reset to zero. This is a reasonable institutional assumption, since the ‘reset’ only applies to conflicts that are not protests - even the most diligent government departments eventually have to clear their desks of non-critical complaints. None of the conflicts encountered in any of the runs were formal protests, which would have activated dispute resolution activity in the CHJ and prevented the register being reset to zero.

The steady increase in conflict with time is happening regardless of what the government does or what the state of the climate is. This is reinforced by the fact that the status quo, the no-change scenario (Scenario 1) also experienced reasonably high levels of formal and informal conflict. This suggests that the system is strongly predisposed to conflict, and that conflict is not being resolved over time.

The significantly higher levels of conflict for the ground water banking scenarios relative to the non-banking scenarios is difficult to immediately explain. There was certainly no direct, coded link between participation in the bank and personal propensity to launch conflict. What this relationship is most likely due to is some secondary factor: higher hydraulic stress might induce an agent to think about participating in the bank to make more water available, and higher levels of stress might also induce the agent to complain informally or formally. It is unlikely that participating in the bank itself would lead to higher conflict, unless conflict was the result of higher social stress induced by agent inability to participate (application denied, for example). A glimmer of support for this argument comes from point 4 in the summary, where the banking scenarios showed their highest stress levels early on, when little water was in the bank and the rejection rate would have been high. Unfortunately, data on rejection rates were not collected so this line of reasoning cannot be pursued much farther.

An important and interesting result is that there appears to be a stronger relation between institutional change and conflict than physical change. Superficially, this is difficult to understand, since it is climate that has some of the strongest controls on water availability, which is in turn a strong determinant of agent stress and propensity to complain. However, it is more explicable when we consider the large number of algorithms that implicated institutional components - selecting bank participation, participating in the bank, reacting to the results of participation, reacting to government interference, and so on. In other words, while climate was an important factor, the agents were far more sensitive to institutional change and action. This is less a function of the society being modeled and more a function of the distribution and density of change in the model: the most frequent change was institutional. What is clear from the data is that the confluence of both physical and institutional change did not necessarily lead to the greatest level of conflict, which in some ways is a heartening result.

5.3.3.2 ... Summary 2-B

1. The bank was clearly functional across all years of the scenarios that simulated ground water banking.
2. The highest lease volumes across all scenarios were encountered in the first five years of the simulation, with considerable fluctuation in lease volumes thereafter.
3. The highest lease volumes in each year were encountered at the beginning of each year, followed by much more minor peaks later in the year.
4. Scenario 3 shows the highest average and total lease volumes.

5. Scenarios with the highest degrees of institutional change showed the highest lease volumes, vice versa for scenarios with only moderate degrees of institutional change.
6. Neither deposits or leases show any clear increasing or decreasing trend, but there is a possible trend toward increasing volumes over time in the deposit data.
7. Deposits show less variability than leases, but the same intra-annual pattern of variability.
8. Scenario 6 experienced the highest average and total deposit volumes.
9. Deposits greatly exceeded leases in average and total volumes.
10. Variation in lease volumes between scenarios follows the same broad pattern seen in inter-scenario deposit volume variation.

The initial peak in bank participation, early on in the simulation run, was preceded right at the beginning of the simulation (first year) by the lowest peaks encountered in either leasing or depositing. This chimes with what one might expect: as agent trust in the bank increases, and risk aversion decreases following successful participation, lease and deposit actions would increase in frequency and volume. Little specific trend can be identified overall, which suggests that year to year variations in participation may depend on a number of factors, including but not limited to climate. The annual pattern of initial peak followed by much smaller peaks tapering off in the remainder of each year, is reasonable given the institutional set up of the bank: agents were only allowed to participate once a year, and the opportunity for participation became available each year after October 1. It is to be expected, given natural stochastic variation in agent cognition, that the majority of agents that wanted to participate, would participate as soon as the opportunity was available (note that the timing of participation was not a factor in agent decision making) and the remainder who didn't want to participate right at that point in time would eventually apply for a lease or deposit.

One of the most interesting results is the stronger relation between institutional change and higher lease/deposit volumes, relative to their relations with physical change. This is not to be unexpected: scenarios with higher degrees of institutional change experienced far more government interference in agent decision making, interference which can directly influence the volumes of leases and deposits (by forcing more agents to participate). Remember, however, that even if such interference led to increased volumes moving into and out of the bank, it came at cost: the social conflict generated for these scenarios was high.

The position of Scenario 6 as having the highest average and total deposit volumes is unusual. Since deposits were mostly by foregoing pumping, one would expect that under a scenario of extreme climate change and extreme government interference, that agents would deposit the most (i.e. forego the most pumping) - in other words, we would expect Scenario 9 having the highest average and total deposit volumes. It is more understandable that Scenario 3 have the highest average and total lease volumes, since Scenario 3 experiences no climate change and so more water was available in the system. At root, this may be due to a complex interplay of stress (and other cognitive variables) with the degrees of government interference and climatic change, a relationship not immediately evident.

It is not surprising that deposits greatly exceeded leases in volume and frequency. Deposits are far ‘easier’ to make, since no pumping is required (by definition: most deposits involved foregoing a pumping right), and the chance is good that the depositor will get some recompense for its non-pumping. Leasing, on the other hand, involves cost both to actually purchase the water and also to pump it. As pre-specified in the code, deposits yield more positive feedbacks than leases. So it is to be expected that deposits will outweigh leases in volume and frequency. However, deposits are no good if nothing is being leased. Leases (purchases) are required to actually pay the depositors. So we can see that despite the presence of more positive feedbacks for depositing, this did not lead to a run on deposits followed by a crash (because of no leasing and therefore no payback on deposits). Point 10 shows that there is some relation between the two activities, so it is clear that leasing and depositing cannot each continue in a vacuum from the other. There may be some cognitive tweaking needed to adjust the balance between deposits and leases, or this may in fact reflect an inherent imbalance (and potential problem) with ground water banks that do not mandate more balanced deposit/lease ratios.

5.3.3.3 ... Summary 2-C

1. Sustainable scenarios, where aquifer levels increase, include 2, 3, 5 and 6. Unsustainable scenarios, where aquifer levels decrease, include 1, 4, 7, 8 and 9.
2. All scenarios show an initial sharp decrease in aquifer levels, but then diverge.
3. Rates of decrease and increase over time are steady.
4. No correlation is identified between frequency of bank transactions and aquifer levels
5. The sustainable scenarios appear to be more strongly associated with higher deposit volumes, whereas the relationship for leases is less clear.
6. Aquifer levels are generally strongly correlated with extremes of precipitation and temperature, and more significantly so with precipitation. The best correlations are found for the scenarios experiencing the most extreme levels of climatic change.

Given the theoretical impact of climate change on aquifer levels, it is no surprise that the most unsustainable scenarios were those experiencing the most extreme climate change. Similarly, the fact that the zero institutional change scenarios (1, 4 and 7) were also in the unsustainable bracket is easy to explain: the status quo was pre-specified to be unsustainable (as it is in the real system), because farmers are consistently extracting water from the aquifer at rates exceeding recharge. Given this reality, and given that the moderate and extreme institutional change scenarios were generally associated with more sustainable aquifer outcomes, there seems a reasonable case to be made for the positive effect of ground water banking on the state of the aquifer over time. The shape of the traces for aquifer level are also supportive of this: all traces show initial (<1 year) slumps steeper than the remainder of each scenario. These initially fast rates of change downwards recover much quicker in those scenarios that had higher levels of institutional interference, suggesting that the ground water bank began to have an effect on average aquifer levels after a time lag of 1-2 years. This is exactly the kind of lag expected: when I speak of ‘average aquifer levels’, I mean exactly that - the average meters above datum across all aquifer cells. However, the actual volume in any one cell will most likely differ slightly from its neighbors, and probably differ greatly from those cells on the opposite side of the grid. This is because, as outlined earlier, anthropogenic effects on the aquifer propagate from a point concentrically out across the aquifer. A pumping event in one corner of the aquifer will eventually affect all cells, but only after many time steps have elapsed. With these inbuilt lags, mounds and troughs of ground water can build up. Consequently, it will take a prolonged positive recharge effect of the banking system to cause across-aquifer increases sufficient to raise the aquifer average. The substantive effect banking had is clear: deposits exceeded leases in volume, and so the bank took offline a great deal of pumping which would have otherwise occurred, improving the recharge/discharge balance in favor of recharge.

The lack of correlation between transaction frequency and aquifer level suggest that volumes of individual transactions are highly variable, and that the controlling factor is therefore less how many agents are participating, but how much water those participants are depositing or leasing. However, since no histogram data was gathered for the range of lease/deposit volumes, this cannot be confirmed.

The strengths of correlations between climatic variables and aquifer levels are no surprise. Precipitation is the largest contributor to the aquifer in the system, and temperature has effects on everything from direct evaporation rates to agent usage of water. Recall, however, that the greatest correlations between aquifer level and change are for institutional and not climatic change. It appears that both types of change have an effect, but these are not always equal.

5.3.3.4 ... Summary 2-D

1. Average stress increases over time for all scenarios.
2. Scenarios are grouped by stress: Scenarios 1, 4 and 7 with lower stress on average than the other scenarios.
3. Average stress has distinct but uneven annual cyclicity (increases and decreases).
4. Average stress increases at a faster rate to begin with than towards the end of the simulation.
5. Social stress shows the same groupings as for average stress, with a faster rate of increase at the beginning of the simulation.
6. Economic stress shows significant variation among all scenarios at the beginning of the simulation.
7. Economic stress shows similar cyclicity and groupings to the other stress types, but a different overall trace.
8. Hydraulic stress shows similar cyclicity and scenario groupings to other stress types.
9. Hydraulic stress for all scenarios except 1, 4 and 7 decreases over time, with annual variation.
10. Scenarios 1, 4 and 7 show the strongest correlations between conflict and stress, but all scenarios show some evidence of a correlation.

11. Average agent fear of government and trust in government both decrease over time, but trust in government enjoys a brief sharp peak in the first two years of the simulation, followed by a fast then slower rate of decrease.
12. There is little evidence that fear of government trust in government have any sort of correlation with ground water banking activity.
13. There is strong correlation evidence that as sociability increases, social stress decreases.
14. There is reasonably strong correlation evidence that as sociability increases, conflict decreases, particularly so for Scenarios 1, 4 and 7.
15. For Scenarios 1, 4 and 7, agent perception of water availability decreases steadily throughout the simulation. The other scenarios show a decrease until year 10, and then a slow increase.
16. Intra-annual variability in perception of water availability is much higher for Scenarios 1, 4 and 7 than for the other scenarios.
17. All scenarios experience a dramatic increase in perception of water availability within the first year of the simulation.
18. Water conflict appears to be sensitive to agent perception of water availability only in Scenarios 1, 4 and 7.
19. Capital is strongly negatively correlated with societal conflict, particularly in Scenarios 1, 4 and 7. Debt is more weakly positively correlated with societal conflict across all scenarios

One particularly clear trend can be drawn from the analysis of the stress data: the less the institutional change, the less the amount of stress the agents are under. Increased interference by the government, and increased requirements to participate in the bank, will lead to greater individual stress. However, in the moderate institutional change scenarios, no government interference exists apart from making available the option of participating in the bank. The CHJ agent does not mandate participation at that level of change. Yet the very presence of the bank appears to cause an increase in stress levels. This may be because of the pervasive effects of hydraulic stress: participating in the bank can raise or reduce hydraulic stress levels depending on the transaction type, volume and whether or not it is approved. It seems the simple act of adding a banking institution to the system increases stress because it increases the transaction costs to agents, and the potential for risk to adversely affect their water situation.

Economic stress among all stress variables shows the most inter- and intra-annual variability. This is probably due to linkages between economic stress and dynamics beyond those of the hydrologic system. The model was parameterized with historical and projected economic data, and so captures the contribution of both exogenous economic conditions. This introduces new elements of variation and uncertainty, and the economic stress variables in agents appear to be reflecting this.

It is important to note how hydraulic stress decreases over time for all scenarios except those without ground water banking. It is difficult to make unequivocal linkages between dimensions of such a complex system, but this does suggest that the ground water banking - some indirect or direct effect of the institution - is working to reduce hydraulic stress. The general relationship described in Point 10 is not surprising: higher stress is the primary precursor to conflict. More interesting is the lack of correlation between agent perception of government and volume of participation in the ground water bank. This may be because the agents are not fundamentally equipped to defect on mass from government requirements. A small percentage will not change an agent’s behavior even if ordered to do so by the CHJ agent, but most will. For most agents their opinion of the government is largely irrelevant to their participation in the bank - particularly if they are forced to participate.

It is clear why sociability is negatively correlated with stress: one of the few direct feedbacks encoded for sociability is a response to stress. The higher the level of social stress that the agent feels, the higher the probability that the agent’s inclination towards communication and interaction will decrease. The apparent correlation between sociability and conflict is less obvious, but is probably a by-product of the positive correlation between stress and conflict. As described earlier, sociability is a principal control on the distance a rumor will propagate in the agent population. As for GWBSIM, which value the rumor contains (from the full range of internal resources of the agent) is randomly selected. Therefore, it is theoretically possible that a rumor of higher stress levels (which is certainly technically possible) propagated exceptionally well and caused overall stress levels to rise; this would correlate with reduced sociability as receiving and passing on a rumor incurred a cost for each agent. The mechanism is somewhat tortuous, however, so I would prefer the explanation that a higher stress reduced sociability by exploiting a pre-specified feedback.

A final nail in the coffin for the non-banking scenarios is the steady reduction in agent perception of water availability relative to the banking scenarios. While all scenarios are dominated by decrease, banking scenarios show some sign of a recovery after year 10. This may represent the delayed feedback of recovering aquifer levels in the banking scenarios: as agents find that water levels are creeping higher in their wells, they will respond favorably by reducing stress and increasing their perception of water availability The non-banking scenarios also experience more significant intra-annual variation, and stronger correlations between perception of water availability and conflict. This higher sensitivity to water availability in the non-banking scenarios could be indicative of a broader feature of these scenarios: in the absence of an institutional mechanism to deal with water scarcity, and the potential additional income this can generate, agents become more dependent on their perception of water availability for their stress levels and so have a higher propensity to generate conflict. Non-banking scenarios are consequently less robust to changes in the physical system (more affected by climate change), whereas the banking scenarios appear to be more dominated by stress and conflict due to the institution of ground water banking itself.

The brief exploration of the financial data suggests strong but inverse relations between capital and conflict. This contrasts with the much more uncertain relations between debt and conflict, where correlations are by turn positive and negative. It is not surprising that conflict and capital are reasonably strongly connected: agent cognition is set up to be very sensitive to changes in agent capital, since making money and making more money is the primary goal of the Farmer agent. Debt is less strongly pre-specified, and so the lack of correlation is expected.

5.4 ... Comparative Analysis, GWBSIM and AlbAgent

A direct comparison between GWBSIM and AlbAgent data is not strictly possible. GWBSIM and AlbAgent are models of different systems that run on different time steps (GWBSIM: daily; AlbAgent: weekly), different time periods (GWBSIM: 5 years beginning in 1980; AlbAgent: 14 years beginning in 1997), different agent typologies (GWBSIM: 5 agent types; AlbAgent: 2 agent types) and significantly different hydrogeological models (GWBSIM: response functions; AlbAgent: bathtub model). Indeed, model differences (and different success in collecting data) mean that there are, in fact, only limited grounds on which the two datasets can be compared: data comparison would not be appropriate. With this in mind, I will conduct a limited comparative and generally qualitative analysis of the two models, highlighting the areas where the two datasets were most similar and, conversely, most different, and any general conclusions to be drawn from these similarities/differences. A brief discussion follows each highlighted difference and/or similarity.

Difference 1: conflict and ground water banking

GWBSIM and AlbAgent generated very different outcomes from the perspective of conflict. In GWBSIM, the banking scenario generated significantly less conflict than its non-banking scenario. For AlbAgent, social conflict was significantly higher for the banking scenarios than the non-banking scenarios. But in both cases, there is strong evidence that the ground water bank led to changes in conflict dynamics.

This is a major and critical difference, providing strong support for the major hypothesis: a dynamic linking the banking system with conflict clearly exists in both models, even if the sign of the dynamic is different in each case. It is not certain why the difference exists. One possibility is in the nature of the pre-specified response of each model's agents to government action. The GWBSIM model attempts to capture the more laissez-faire government model in the western United States, by not allowing for much government interference beyond setting the price per unit water. The AlbAgent model, on the other hand, attempts to capture the much more interfering and didactic tendency of a European government in regional water operations. This has meant significant cognitive differences for agents between the models. Agents in both GWBSIM and AlbAgent have environmental, economic and social sensitivities that affect the state of their internal stress variables. But AlbAgent agents have many more opportunities to resent government involvement, and experience higher stress levels on a social front due to that involvement, because the government agent is by its very design inclined to step in more often. It is telling that hydraulic stress in AlbAgent goes down for the banking scenarios, while the social stress goes up - the problem is not the bank itself, but additional interference that the extra institutional capacity represents.

Difference 2: severity of conflict

GWBSIM experienced the highest level of conflict possible in the simulation - court action - while AlbAgent did not experience a single conflict of comparative severity.

Without conducting extensive comparative runs to explore the sensitivity of outcomes to agent conflict action thresholds, it is difficult to say conclusively whether or not this difference is due to finer points of cognitive design within each agent, or whether it is in fact due to some fundamental difference in the response of the model to ground water banking.

Difference 3: bank performance

GWBSIM showed a much more consistent rate of increase in deposit volumes over time than AlbAgent, which was largely devoid of any particular trend either for deposits or for leases. Furthermore, GWBSIM's deposits increased steadily over time, whereas AlbAgent's deposits peaked early then showed variation with little clear trend.

This is most likely rooted in the different population structures for each model. GWBSIM had several different basic irrigator types, whereas AlbAgent had just one. Among the GWBSIM irrigator types was an economically strong, infrastructurally-equipped agent that had water to spare and little risk even if no payment was forthcoming for deposits. This irrigator type dominated the statistics for bank performance, since this irrigator was reasonably insensitive to vagaries in economy and the environment. The Farmer agent in AlbAgent, on the other hand, was the only agent type interacting with the bank, and much more sensitive to economic, social and environmental change when selecting the volume of a lease/deposit proposal. Possible affecting this is the design of agent cognition in GWBSIM: deciding to participate and then choosing an appropriate lease/deposit volume was conducted as a separate action once a year, including a consideration of a broad variety of factors not restricted to hydrologic concerns. In AlbAgent's simpler cognition, the same process was included within the irrigate() algorithm (potentially called every time step, depending on the agent's crop type). For AlbAgent agents, deciding to participate in the bank is strongly tied to immediate hydrologic conditions, which are themselves highly variable. Consequently, AlbAgent agent decisions are less robust to hydrologic variation at decision time, leading to more of a punctuated equilibrium than the steady trend exhibited by GWBSIM.

Difference 4: intra-annual variation

AlbAgent results displayed much more dramatic intra-annual variation, across most measured variables, than seen in GWBSIM.

There are two major sources of potential annual variation in AlbAgent: the annual crop planting/irrigating/harvesting cycle, and processing of conflicts by the government agent (CHJ). The annual crop cycle could potentially influence conflict, since the process of choosing, planting, irrigating and harvesting a crop requires that the agent make a number of decisions that assess its perception of water availability, and involve communication with other agents - which could lead to changes in internal state that promote conflict generation. Remember that in both GWBSIM and AlbAgent, conflict-potential assessment is undertaken every time step, so there is no annual variation attributable to the simple fact of assessing whether complaining is a good course of action. Most of the crop cycle decisions that will influence stress and other conflict-critical variables in AlbAgent are taken at the beginning of the year, so this could help explain the peak in stress variables at this time. Note also that, since some of the agent crops (e.g. olives, vines and fruits) may run on less than a 52 week harvesting cycle, this could help result in some of the smaller peaks of stress and other cognitive activity seen during the year. The second possibility is that the action of the CHJ agent to reset its record of conflict each year is introducing some significant and unnatural annual periodicity to the system: all agents have some awareness of the global level of conflict, and this awareness they receive from the CHJ agent. Their awareness of conflict in the society at large is tied to their own stress levels and in turn the likelihood that they will complain and add to the global level of conflict. It is further possible that this cyclical change in awareness of conflict is having unknown knock-on effects to other cognitive variables: for example, the range of cognitive variables that includes water availability, since these show a particularly strong tendency to annual variation.

A problem with the first explanation is that GWBSIM has a similar annual cycle in crop selection, planting, irrigating and harvesting. In fact, this cycle has a much stronger annual basis, since there are no crops that have a less than or greater than 52 week cycle. It may be that the resolution of data analysis is simply not good enough to show up more detailed annual variations (most datasets gathered from GWBSIM runs were averaged across months or years), or it may be the case the fact that AlbAgent's annual reset of conflict does not exist in GWBSIM.

Similarity 1: deposit/lease balance

In both GWBSIM and AlbAgent, participation in the ground water bank was dominated by deposit transactions. The volume of deposits in both models was up to double that of the volume of leases made.

The basic theory behind this form of bank performance in both models is similar: deposits are less risky and carry greater potential payoffs than leases, and so provide far more positive feedbacks to early adopter agents who then spread the word and re-deposit themselves the following year. The problem in encouraging leasing was discussed at length in the GWBSIM data analysis, where it was found that a combination of low risk, higher payoff and the restriction of leasing until the second year of banking led to a permanent and sometimes worsening imbalance between leases and deposits. However, since the same year 1 moratorium on leasing was not present in AlbAgent, it appears that even if deposits and leases are permitted from the very beginning, the system is still predisposed to weight deposits more than leases. It is debatable whether a real banking system in either setting would have a more rapid feedback: one would expect the lack of payback on deposits to lead, within a year or so, to rapid reductions in deposits as individuals realized the imbalance. However, this does not factor in the importance of cognition: in GWBSIM, trust in the bank and happiness with the transaction costs were important cognitive variables probably influencing the number of agents who came back for more. Nor does it factor in the fact that depositing agents in GWBSIM were stronger economically and hydrologically, and so could afford a few years of loss particularly if participation made them feel better about the imminent risk of an ESA listing. In AlbAgent, similar ‘fear’ variables were in action: all agents had some variable relating to ‘fear of shutdown’, or other fear of government action that might reduce the amount of water available to them. Consequently, behaviors should have been oriented towards reducing the level of fear, and participation in the bank had a feedback that would reduce the agent’s perception of its shutdown risk. This would give positive feedback for future participation even if other feedbacks (e.g. rate of return on investment) were negative. Leasing does not have the same confluence of cognitive feedback and favorable agent typologies: leasing is accomplished on an as-needed basis, and does not represent any sort of investment either in hydrologic terms (so that more water is available later) or in social terms (so that the government doesn’t shut you down). It also costs more, and so requires a stronger commitment and higher cognitive thresholds to conduct. While it is interesting and instructive that both models display qualitatively similar behavior for lease/deposit balances, it is not clear why the imbalance was typically in a ratio of 2:1. This is something to address in future work.

Similarity 2: role of economic conditions

In both GWBSIM and AlbAgent, higher levels of capital equated to lower levels of conflict. In both models, debt had more of a mixed role, sometimes positively and sometimes negatively correlated with conflict.

Money, in effect, makes the agent models go round. Many agent activities are at least partially undertaken to make money, and more of it if possible: the crop cycle, selling land or water, participating in the bank, etc, all have potential economic benefits that the agent is hardwired to pursue. In this sense, the strong connection between capital and conflict in both models is entirely predictable: the drive to maintain and increase capital is hard coded for all agent typologies barring the government actors, in the form of positive feedbacks for actions that benefit capital, and negative feedbacks for actions that cost capital. In this way, a reduction in capital does not in and of itself lead an agent to go to court (or protest, in the case of AlbAgent), but will raise its stress levels and affect other cognitive variables in predictable ways that will raise the probability of the agent eventually complaining or going to court. Debt is not hard coded to influence agent behavior in the same way, so it is also understandable that debt is less clearly associated with conflict. It does have some effect on stress in both models, but in not as many places or with as significant magnitude compared with capital. The importance of capital in relation to conflict raises the specter of calibration of models with such complex and detailed social components. For both GWBSIM and AlbAgent, the connection between capital and conflict is indirect and not deliberate, but the dynamics between capital and stress are very direct and very deliberate. The strength of the feedback, which is generally parameterized by the modeler although it may fluctuate during the model and be modified stochastically at runtime, is something that has to be derived from some sort of social investigation either with primary or secondary source material. In the case of GWBSIM, this material was extensive interviewing with local stakeholders and expert testimony as to agent motivators. In AlbAgent’s case, this material was mostly just expert testimony and literature review. Was the assumption of close connections between capital and stress in GWBSIM also valid for AlbAgent? We should acknowledge at this point that, despite the complexity of these systems models and the high potential for emergent behavior due to unforeseen and unspecified interactions between model components, it is still very likely that the hand of the modeler will show in the results.

Similarity 3: baseline conflict

Results from both models show that the baseline conditions - no institutional and environmental change added - experienced often not inconsiderable levels of conflict.

Superficially, this is evidence to support the argument that both models are adequately calibrated and validated. Both real world systems are afflicted with conflict at the present time, albeit to varying degrees, and so the reproduction of the existence of conflict by the baseline scenarios in both models is heartening. It raises the probability that the fundamental setup of each model is a reasonably true approximation of reality: both eastern Idaho and eastern Spain suffer conflict and water scarcity due to over-allocation and worsening climatic outlook. The models do a reasonable job of reproducing those conditions - agents competing for a finite resource, climate worsening over time, and conflict being generated as a result. Remember that there is no hard coded, direct relationship between the struggles of agents and conflict. Nowhere in either model's specification is any direct algorithmic relation listed that would directly connect the amount of water an agent has with the amount of conflict it generates. The models both make indirect connections by making the assumption that agents are predisposed to become stressed when they have less water, and a higher level of stress (plus other contributory factors) will raise the probability of the agent going to court or otherwise generating conflict. But to the credit of both models, the conflict generated in the baseline scenarios is generated purely as a result of the basic interactions of agents, which is partly controlled by the initial parameterization of each model. To paraphrase Epstein and Axtell (1996), conflict in both GWBSIM and AlbAgent is grown and not made.

It is also possible to interpret this similarity as evidence that complicates the assertions made so far regarding the major hypothesis. Discussions so far have addressed the evidence that more institutional change wreaks some sort of change on the severity and/or frequency of conflict in an artificial society. The fact that in both models the baseline scenario is highly conflicted suggests that I can only support the major hypothesis as far as it applies to systems that are already experiencing conflict. Neither model helps us much with the case of a system that is already in a conflicted state. Since the focus of the thesis is on such systems, this might seem a moot point. But consider the implications for a water manager: not only is she likely to be interested in seeing the effects of an expansion in institutional capacity on the current level of conflict, but she will also be curious as to the effects of the expansion on any dimension of a system that is not already conflicted. While this analysis does not materially change anything from the perspective of the thesis, it does add some sideboards to the real world relevance of any conclusions drawn.

5.5 ... Discussing results from the perspective of the Sub Hypothesis

Hitherto, the sub hypothesis has been barely discussed. As a reminder, this asserted that "institutional and environmental differences between modeling settings do not necessarily mean that a fundamentally new socio-hydrologic agent must be built for each". What light do the results for both models shed on this hypothesis? Note that for the purposes of testing this hypothesis I set out in AlbAgent to build the same - or similar - cognitive engine used in GWBSIM, using the very same code wherever possible.

By the principle of falsifiability, one can never conclusively prove a hypothesis, merely reduce the probability that it is wrong. On the other hand, we can conclusively prove a hypothesis wrong: I begin this discussion by determining whether, despite setting out to construct similar agent cognitive engines in each model, I in fact created AlbAgent cognitive engines fundamentally different from their counterparts in GWBSIM.

The comparative analysis just completed shows considerable difference and considerable similarity between the results from each model. Many of these differences at least partly stemmed from fundamental differences in content and structure between the representation of irrigators in each system. Consequently, the discussion identified several areas of significant difference that relate to the cognitive models used in each. For example:

- The greater complexity of the GWBSIM cognitive model, in terms of larger numbers of cognitive variables, and more sophisticated processing of IF-THEN rulesets
- Variation in location and severity of feedbacks from the results of actions/thoughts onto cognitive variables such as stress and social capital.
- Less significant role for emotional variables in AlbAgent (fewer of them and fewer feedbacks from and to agent action).

While I can assert that the basic concepts of all agents in both models are derived from the Belief-Desire-Intention cognitive architecture, some fundamental structural differences do exist:

- AlbAgent makes use of far more pre-processing of intentions prior to selecting an action. The 'temporal tag', 'concept' and 'intention' filters allow the average AlbAgent agent to conduct a much faster binary search of the action space than the equivalent agent in GWBSIM. All of GWBSIM's agents have to check for the activation condition in all possible actions every step of the model run. This imposes a performance overhead, but also means that some actions which would be weeded out earlier though AlbAgent's hierarchical selection process will slip through the net in GWBSIM (due to stochastic components in its decision making) and so will change the behavior of GWBSIM agents.
- GWBSIM makes use of fuzzy logic to process large numbers of IF-THEN rulesets into action. AlbAgent makes use of a weighting process, where particular outcomes are weighted according to an assessment of influencing conditions. The contribution of positive and negative influences for a particular outcome are

weighted such that it requires a majority of positive or negative influences before one action or the other is taken. The process of selection is a great deal more stochastic at the action-selection level in AlbAgent (but note that it has already narrowed the field considerably more than GWBSIM by that point), and a good deal less sophisticated: far fewer condition-action pairs are evaluated.

- The different structures for processing intentions into actions via condition evaluation mean that there is a significant performance benefit for AlbAgent and a significant performance cost for GWBSIM. This, in turn, means that other components of agent cognition - such as memory and learning - can receive more processor and memory attention in AlbAgent than they do in GWBSIM. One of the reasons the GWBSIM runs ended up being 5 years rather than 20 is that the time needed to complete the full runs (over 5 hours) and the memory required to keep the Java heap from overflowing (around 2 GB) was prohibitive from a logistics standpoint. The smaller, leaner cognitive model of AlbAgent does mean that actions are taken via the evaluation of a much smaller number of conditions, and so there will likely be significant differences in the adaptability and the richness of agent behavior. But it does also mean that more runs can be completed and more analysis conducted on more data.
- The nature of the memory structures in AlbAgent and GWBSIM are different. In GWBSIM, memory is a simple store-and-retrieve arrangement, with little temporal sensitivity (a corollary would be a single read/write action per memory type - every time something is written to memory, it erases the previous memory of that same type). In AlbAgent, memory has better indexing, so that a specific year in the past can be selected, and new memories added without overwriting old memories. The difference reflects what was mentioned earlier, in that more resources (both processing and memory) could be devoted to memory in AlbAgent than were available for the same in GWBSIM. In fact, the AlbAgent memory structure was attempted in GWBSIM, but led to a major memory leak and so had to be discarded.

Do these differences fundamental, or are they merely tweaking the technical details of the same conceptual model? I would argue the latter. Agents for *both* models process a set of beliefs into a set of intentions (or plans), and then select from the viable intentions at any one time a particular preferred intention, before processing that intention into an action, and finally taking the action. Results of the agent's own and other agents' actions feed back into beliefs and so affect future actions. Stripped down to their basic structure, cognitive models in both GWBSIM and AlbAgent are similar enough that no new theory had to be implemented in code. In fact, AlbAgent is more of a Version 2.0 to GWBSIM's 1.0: the development of GWBSIM preceded AlbAgent by several months, and so experience from the development of GWBSIM informed the development of AlbAgent. The design process for AlbAgent took the basic concept settled upon in GWBSIM, and attempted to implement the same basic concepts but with more efficient and effective coding. The question really, then, is what is really meant in the sub hypothesis by "fundamentally new". Does the same concept but a new technical implementation count as a fundamentally new agent?

To answer this, we must consider whether the differences in model behavior induced by the technical differences listed above were significant enough warrant characterization as “fundamentally new”. The following list is discussed considering AlbAgent relative to GWBSIM.

- *Less cognitive complexity*: this generated simpler, less adaptive behavior, but nothing new.
- *Fewer, more dispersed feedback points*: AlbAgent feedbacks were fewer and farther between. This led to less sensitivity of AlbAgent agents to changes in their external environment. The one area where this perhaps had the most effect was in the acuteness of conflict experienced by each model: maximum level in GWBSIM, and only the moderate (‘formal complaint’) level in AlbAgent. With more and denser feedback points from agent action/observation to agent emotion and thought processes, it is likely that agents would have been more sensitive to external stressors. However, while this would potentially change the maximum level of conflict experienced, it does not create any fundamentally new behavior.
- *Less emphasis on emotional variables in AlbAgent*: relative to GWBSIM, AlbAgent used far fewer emotional variables (where ‘emotional’ covers internal resources that were not related to tangible external resources, e.g. happiness, stress). This was more a result of limited development time than intentional reductions. It is true that adding or removing anything (including variables) from a facsimile of another model will render that model no longer a facsimile but a unique creation - and with unique model outcomes as a result. It was clear from the analysis of GWBSIM results that its emotional variables had no significant influence on the outcome of the model. This is probably partly the result of a deliberate engineering decision: uncertain about the validity of embedding such subjective (and sometimes controversial) components into agent cognition, and mindful of the problems in calibrating such components, I deliberately underweighted the influence of change in emotional variables on any other variables or actions. So if these variables are added or removed, they are less likely than most other variables to cause any significant change in agent behavior. In other words, by removing emotional variables from the array available to agents in AlbAgent, it is unlikely that I made any great change to the model outcome. Consequently, I hazard that this does not provide strong evidence that the models differ *significantly*.
- *More pre-processing of intentions prior to action selection*: this reduced the processing and memory footprint of the model, but did not fundamentally change agent behavior. One minor change would have been in the degree of stochasticity in action selection, since GWBSIM agents incorporated a wider search of the potential action space than AlbAgent agents, allowing for greater opportunities for chance selection of actions inappropriate if we assumed purely rational decision making. In other words, AlbAgent agents probably behaved in a marginally more predictive way. But note, this is a purely qualitative assessment without strict quantitative basis.
- *Use of a weighting process versus fuzzy logic for selecting between IF-THEN rules*: this certainly reduces the richness of responses for an AlbAgent agent, but does not change the fundamental way the agent behaves. An AlbAgent agent assess current conditions, and takes action if the conditions meet a certain combination of stored rules. This is exactly the same behavioral approach taken by GWBSIM agents, only

these agents have a larger ruleset to choose from, more powerful algorithms to sort through the ruleset, and more sensitivity to variation in precursor conditions.

- *Increased emphasis on memory versus active cognition*: AlbAgent possesses greater ability to store and retrieve data than GWBSIM. This does have the potential to significantly change behavior, but does not make any real change to the way the agent makes decisions. Consider an example: a typical decision point in both models is the choice an irrigator faces between irrigating or not irrigating. In GWBSIM, the irrigator might factor in what the current temperatures are associated with (in annual terms). Does a 45 degree high at this point in the year mean that a drought has followed in the past? GWBSIM agents' primitive memory could only consider the last piece of data stored covering 45 degree days and what subsequently followed. If the last year happened to be a non-drought year, even though all the preceding years were serious drought, the agent would underestimate the drought probability. In AlbAgent, on the other hand, each agent would have a better recall of the drought years and so perhaps be more inclined to adopt a more conservative irrigation strategy. In either case, the fundamental strategy has not changed - using memory of past conditions to influence current decision making - even though the actual decision is different. In passing, I note a point made by Van Lehn (1991), who suggested that one cannot ascribe a different cognitive architecture to an entity on the basis of a limited snapshot of its behavior.

From these arguments, I propose that the cognitive agents used in GWBSIM and AlbAgent, despite significant differences in technical implementation (the code for each would look very different if compared), are not different in terms of fundamental cognitive architecture.

I am advancing that the same conceptual approach to agent cognition in two or more different models, even if their technical implementation differs widely, will result in reasonably similar fundamental behavior between agents - where fundamental behavior is that behavior which is independent of parameterization, i.e. how an agent makes decisions and not what decision the agent actually takes in any given situation. The sub hypothesis posits that it is not necessary to build a completely new socio-hydrologic agent for each setting; with my concept of 'difference' in mind, we can re-word the sub hypothesis: it is not necessary to adopt a completely new *cognitive architecture* for agents between different socio-hydrologic settings. 'Cognitive architecture' in this instance refers to the basic principles around which the decision making algorithms of an agent are organized. I can now ask the question, given the results generated by GWBSIM and AlbAgent runs: *should* I have adopted a completely different cognitive model for AlbAgent agents versus GWBSIM agents? In other words, was the cognitive model adopted for AlbAgent in any way deficient relative to GWBSIM? If the model was indeed deficient, then the sub hypothesis would not be supported, because of the implication that AlbAgent's different setting required a fundamentally different cognitive architecture.

I will begin with attempting a brief analysis of the fundamental institutional differences between the two settings. As discussed earlier, this was the area of most significant likely difference between the two settings, since on climatic and hydrogeologic grounds they are remarkably similar. By delineating the basic institutional differences, I can establish whether there were grounds for fundamentally altering agent cognitive architectures to address these differences. If so, then there is a stronger case to be made that the cognitive architecture adopted for both models was deficient because it did not address these differences. I will use Ostrom's Institutional Analysis and Development framework, since it is actor-focused and a well respected tool for describing institutions and institutional systems. According to Koontz (2003), Ostrom's framework suggests that actions by individuals related to institutions is influenced by the following factors: "(1) attributes of the physical world, (2) attributes of the community within which actors are embedded, (3) rules that create incentives and constraints for certain actions, and (4) interactions with other individuals" (Koontz 2003, 3). I will use these as basic descriptors of institutional setting for the purposes of comparison.

Having found that attributes of the physical worlds in both systems are sufficiently similar for the purposes of coarse modeling as to be discounted in this discussion, what about community attributes? The Idaho irrigation community, despite the fact it is riven by significant legal conflict, is remarkably cohesive and uniform. This is much in common with other western United States irrigation communities, which may dispute ownership and use of water, but generally are similar in economic characteristics, social make-up and political leanings. The Albacete irrigation community seems to share the same level of uniformity and cohesiveness, even though it is a good deal smaller in population (Angelo, pers. comm., 2007). The rule bases that create incentives and constrain actors is the first real area of apparent of difference: in particular, nothing like the Water Framework Directive exists in Idaho. Actors in the eastern Snake appear to be far less restricted by potential government action, and have far greater freedom to use their water as they see fit. However, the difference may only be one of magnitude: the WFD embeds elements similar to components of several major pieces of Federal legislation currently impacting the eastern Snake - the Endangered Species Act in particular. But the WFD remains a paper document with variable levels of commitment from European governments. A similar dynamic could be argued for Federal legislation implemented at the state level. There may, in fact, be more similarities between the institutional rulebase facing irrigators in Idaho and those in eastern Spain than first apparent: both communities face censure by a regional authority; both communities regulate their economic activities at least partly in tune with patterns of national and supranational agricultural subsidies; both communities are driven to use technology to source irrigation water for the purposes of growing cash crops; and importantly, both communities are incentivized to defend their water rights though recourse to political and/or legal action. So in terms of point 3 in Koontz's interpretation of the IAD framework, Idaho and eastern Spain may share more similarities than differences, with the exception of one important area: the history of irrigator relations with authority. While it is the case that both Albacete and Idaho have enjoyed and even expected nationally subsidized irrigation infrastructure, the willingness of the Idahoan irrigation communities to accept government interference not in their own economic interest - and the range of tools with which they can fight that interference - is greater and wider (respectively) than is the case in Albacete.

From this cursory analysis, the greatest area of institutional difference between the two settings appears to be in the resources the institutional setting makes available for agents to fight governmental interference, and the extent to which agents within the system resist interference not in their economic interest. The important question, then, is whether or not the cognitive architecture used in GWBSIM is able to adjust to each setting without fundamentally changing. The adjustment to take account of this difference is, in reality, a simple one: slight change in parameters, a larger range of actions available to the government action, and reduced density of feedbacks between government action and stress/conflict. No major change in the fundamental decision making processes of the AlbAgent agent is required.

Given that it is reasonably clear that institutional differences between the settings are not sufficient to warrant an entirely new cognitive architecture, what about the technical performance of the architecture in each model? I define 'technical performance' as problems encountered in data quality/model performance/agent behavior/system behavior and so on, but clearly localizable to some element of the cognitive architecture. The simple answer is that the cognitive architecture adopted was deficient in *both* models, but no problems with technical performance are localizable to the application of the cognitive architecture to AlbAgent versus GWBSIM. Areas of mutual deficiency included:

- The agents in both model were not as adaptive and responsive as intended in the original specifications. This is primarily because the BDI framework does not provide for more adaptivity in agent behavior than the modeler chooses to hardwire. This is unlike the ACT or SOAR frameworks, for example, which can marshal new information and generate new action at runtime (Anderson 2003).
- The representation of agent knowledge using the 'belief' and 'desire' concepts, while a simple and accessible approach, quickly becomes complex as the number of beliefs and desires spirals. This was particularly true in the case of GWBSIM, and was one of the reasons the AlbAgent implementation was leaner from the start.
- The BDI framework does not provide any sort of guidance as to how to mesh agent learning and memory with its basic framework of knowledge. Since learning and memory were explicit and important parts of agent typologies in both AlbAgent and GWBSIM, this was problematic.

Aside from mutual deficiencies, there were a few areas of different technical performance. But as the following discussion shows, none can be traced to specific problems with the application of the GWBSIM/BDI model of cognition in the AlbAgent context:

- The technical implementation of AlbAgent fell short of providing the richness of agent behavior seen in GWBSIM, even if the conceptual models were very similar. For example, the *irrigate* action in GWBSIM is composed of a number of subroutines, each of which is defined separately. This allows for more dynamic and detailed behavior. In AlbAgent, the *irrigate* method is completely self-contained and does not call any other subroutines. This was a deliberate design change from GWBSIM in order to achieve a leaner codebase, but it did have some implications both for the complexity of agent behavior and ease of debugging.
- Some of the data generated in AlbAgent showed evidence of artificial variability due to the oversimplified implementation of the BDI cognitive model in AlbAgent.

> The intra-annual cyclicity seen in most cognitive variables may well be an artifact of poor integration between institutional and cognitive algorithms. For example, the annual ‘reset’ of conflict records by the CHJ may be having an influence on agent cognition well beyond the likely magnitude of any such effect in the real system.

The bulk of these implementation issues stem from the leaner implementation of the GWBSIM cognitive model, which I would argue is not a fundamental problem with the conceptual framework of agent cognition since it could be addressed by another cycle of development (and would probably fall under a validation task for a longer project). Disregarding these issues, then, there is little evidence that the GWBSIM cognitive architecture, when applied to the Albacete setting, experienced fundamental problems. Without doing more exhaustive testing of the same models with different cognitive engines for each agent typology, it is impossible to say conclusively whether a different cognitive model would have been better tailored to the Albacete setting. But for the purposes of comparison, I propose that the two cognitive architectures not only did not substantively differ, but that the different settings did not require different cognitive models - from both institutional and technical perspectives.

6.0 ... Conclusions

Here I address the two research questions posed at the beginning of the thesis (reproduced below for reference). If evidence has emerged that disproves either the Major Hypothesis or the Sub Hypothesis, I will discuss this in detail; otherwise I will construct brief arguments summarizing the earlier discussions, in favor of the two hypotheses.

6.1 ... Research Question 1

Question 1: Theories exist which suggest that higher institutional capacity correlates with reduced conflict frequency and severity; can agent-based socio-hydrological models of two institutionally rich, conflicted water resources management settings contribute to this theory, and if so, what kind of theoretical relations do they suggest?

6.1.1 … Conclusions on existence of a theoretical relation

The results present a contradiction. The more complex GWBSIM showed that ground water banking had a significant effect on the level of conflict in its artificial society. Comparing the -GWB and +GWB scenario on all significant metrics shows that in the -GWB scenario agents were more stressed and more likely to launch conflict than under the +GWB scenario. Conflict was both more frequent and more severe under the -GWB scenario. Conversely, AlbAgent showed that higher levels of institutional change, which included ground water banking and other government interference in the running of the hydrologic system, were strongly correlated with increases in per agent stress and overall levels of conflict in the system. What does this mean for the major hypothesis? The major hypothesis suggested that, due to tight coupling between institutions and the physical system, that any change in the institutional framework would lead to a change in the level of conflict - via the physical system. While the data from GWBSIM and AlbAgent are somewhat contradictory, the discussion in the Results has shown that there are plausible causative relations between institutional change to conflict outcome. Epistemologically, while there are uncertainties in the data and in the simulation structure, the model is still, at base, a logical model. Consequently, the modeler has complete control over simulation predicates, and unlike other approaches to analyzing complex social systems, agent-based models can communicate strong evidence of causative relations (given initial assumptions). Given the analysis and this epistemological reality, I can confirm the hypothesis:

Institutional change does lead to a concomitant change in level of societal conflict, for two simulated artificial societies. In one case, the change is negative, and in the other the change is positive. But there is most definitely change and the causal link to the expansion in institutional capacity is clear in both cases.

Note that in the following discussion, I occasionally use terminology that implies a human-like intelligence to agents: words like ‘ability’, ‘belief’, ‘see’ and so on. These terms are only meant to be descriptive in the sense of the coded cognitive abilities of each agent. They do not imply real creative intelligence on the part of any agent. For example, when a GWI agent ‘sees’ the ground water bank as presenting an economic benefit, this is only because the exploitation of economic opportunity is a specific behavioral characteristic the agent can adopt from a range of hard-wired options. It does not imply any sort of reflective consideration in the way a human might undertake.

6.1.2 … Conclusions on the nature of the confirmed theoretical relation

In the case of GWBSIM, it is not exactly clear how the ground water bank is having the effect of reducing conflict. The banking system did affect individual variables in a predictable way: for example, it reduced agent stress via a variety of cognitive benefits. However, poor correlations between change in any single variable and the overall conflict outcome suggests that:

The most likely explanation for the reduction of conflict in GWBSIM is a combination of factors interacting in an emergent fashion.

This combination included the financial boost that participation in the bank provided, the positive feedback to key agent emotions caused by successful transactions with the bank, and certain artifacts of the design of the institution itself: GWIs are more likely to participate in depositing because they more often have excess water and are less likely to need to lease water. SWIs are less likely to deposit because they more rarely have excess water, and have a higher risk aversion due to their more vulnerable economic situation. Participation in the bank is thus, by virtue of physical reality and institutional mechanisms, weighted in favor of GWIs and deposits; the data for bank performance strongly supports this conclusion. This system is showing emergent properties (Epstein 2002) because a confluence of factors is acting on the per-agent scale in unexpected ways, resulting in unexpected (could not be predicted a priori) macroscale system behavior.

Similarly, in the case of AlbAgent, it is not fully clear why increasing institutional capacity is leading to higher levels of conflict. This is despite the fact that the level of participation in the ground water bank is - relatively speaking - as good in AlbAgent as it is in GWBSIM. Once again, it appears that:

An emergent mix of factors are acting through local agent feedbacks to generate more conflict when we might expect less.

Higher stress leads to greater propensity to complain but greater motivations to participate in the bank, and a different institutional environment in AlbAgent relative to GWBSIM means that the institution of ground water banking does not have the same role. This last point is critically important to helping us unravel why, for Idaho, ground water banking reduces conflict and why, for Spain, it increases conflict: in the Idaho setting, agents largely participate in the bank primarily because they see a financial opportunity, have excess water to spare, and calculate that the risk to income is not great enough to prevent participation. Fear of future government action is a part of agent motivations in GWBSIM, but these agents experience and emphasize this variable nowhere near as strongly as agents in AlbAgent. In the Spanish setting, agents live in fear of government action at some point in the future; participation in the bank does little to reduce that stress. It may in fact increase stress, which may ultimately lead to more conflict. In the AlbAgent scenarios with more extreme systemic change, agents not only fear intervention but frequently experience it: the government is able to issue ‘shut down’ directives and force new subsidy programs upon the Farmer population. The key dynamic is variation in what motivates agents to participate in the bank. It appears that increases in institutional capacity that do not address the social stressors in the system, will not be very effective in reducing system conflict. I can summarize this discussion by emphasizing the different roles the ground water bank plays in each systems:

- In GWBSIM, the bank acts as an economic and social pressure value, allowing some agents to both make money and allay fears of government action.
- In AlbAgent, the bank acts primarily as an environmental mechanism, improving water availability but causing friction among the community because participation is not necessarily voluntary.

To summarize the discussion so far, we can characterize the nature of the theoretical relations between institutional capacity and water conflict as the following:

Institutional capacity and water conflict are likely to be related for a given artificial society, but the exact nature of the relations (positive, negative or neutral) will depend on the emergent results of the mix of predicate cognitive and economic factors included in the model.

A component of the major hypothesis suggested that institutional capacity might alter system conflict because it would make more water available to those who needed it, mainly by reducing system inefficiencies. Both models provide evidence that contradicts this suggestion. In AlbAgent, ground water banking appears to be wildly successful in improving the state of the aquifer, and so makes more water available. But it does so at the expense of social harmony, greatly increasing the social stress on agents in the system and doing little for their economic stress. Due to data collection problems, GWBSIM’s environmental data is not available, so it is not possible to say exactly what impact the bank had on the hydrologic system (both surface and subsurface). But with significant deposit volumes (a cumulative total of around 4 million acre-feet by the end of the simulation), both river and spring flows are likely to have been positively affected. Even given this likely positive hydrologic benefit of ground water banking, it emerges that one of the strongest drivers to participate in the bank for GWBSIM agents was what the bank represented to the agent type which participated the most. For the GWI agents, with their strong economic position, were able to see the bank as an additional potential economic opportunity. The existence of the opportunity had favorable effects on the agent’s level of stress and knock-on effects on the level of conflict in the system. In some ways, this is not far from one particular view of the problems in the real system. Some stakeholders maintain that it is not hydrologic or climatological problems which plague the Snake, but economic competition between different groups of irrigators and water uses. According to their views, it serves the lower valley well to accuse the upper valley of using too much water, since putting the upper valley out of business through some unilateral state action would mean more economic hegemony for the lower valley. Of course, such sophisticated dynamics are not a part of GWBSIM, but in a crude way the model appears to do a good job of replicating them.

Putting the question in terms that a water manager might appreciate, given the intended corollaries between artificial and real societies: is expanding institutional capacity likely to result in reduced conflict? The answer is yes, but only sometimes, and not always for the reasons one might suspect. In GWBSIM, banking succeeded in reducing conflict because it provided potential for economic benefit, providing additional uses for excess water, and - to a smaller extent - improving absolute availability of water in the system. In AlbAgent, banking succeeded in improving the overall environmental sustainability of the system by reducing over-allocation and making more water available (in absolute terms) to recharge the aquifer. This is an important point which should not be underemphasized. However, one might say that this kind of benefit would not be realized in the real world, because environmental benefits are usually put after resolving social problems. Such was the level of conflict in AlbAgent that one cannot but think that ground water banking would not last long even with such positive environmental benefits. But note: while ground water banking in AlbAgent did not succeed in reducing conflict, this was not because it did not make more water available. It failed because the root of the problem was the level of cumulative stress the agents were under, social, economic and hydrologic. The bank addressed hydrologic stress at the expense of social stress; the institutional solution represented by the bank did increase institutional capacity to handle the basic problem of water scarcity, but not the institutional capacity to handle conflict and certainly not the capacity to address negative attitudes to government interference. A more successful scenario might have been a ground water banking system accompanied by economic incentives (instead of threats) to guarantee a base level of participation, and a changed institutional environment reducing the likelihood of future government action. In some ways, GWBSIM and AlbAgent represent ends of the spectrum with regard to how much the government should step in and influence the operation of the bank. GWBSIM's SME was limited to a very hands-off approach, charged with carrying out simple bank administration. AlbAgent's CHJ, in the most extreme change scenarios, had the power to issue shutdown orders and participation directives, as well as set the price per unit of water in the bank.

To summarize the lessons for a water manager:

- The likely effect on conflict of expanding institutional capacity depends on the nature of the scarcity in the system. If the scarcity is fundamentally hydrologic – there is, on average, less water available for the whole system than is being demanded – expanding institutional capacity will have its strongest effects when the capacity somehow makes the pie bigger (i.e. adds more water, physically, to the system). If the scarcity is fundamentally institutional – there is enough water to go round, but it is distributed badly through inefficient allocation systems –

then expanding institutional capacity may have a much stronger effect on conflict. Where the nature of the scarcity is both hydrologic and institutional, institutional capacity is likely to have moderate effects on reducing conflict, but will not resolve conflict.

- A critical variable that may help determine the effectiveness of a banking system (and any form of institutional capacity expansion) is the degree of government involvement in the expanded system. The appropriate degree of involvement will vary between different contexts, but the median position – using the economic clout of the state to incentivize participation, and perhaps taking a harder stance when necessary to re-balance bank participation – is likely to be most effective in most cases.
- Another critical variable helping to determine the effectiveness of a banking system in reducing conflict is the type and level of a priori social stress the actors in the system are experiencing. We could operationalize "social stress" concretely as pre-existing levels of legal and political conflict, or less concretely as levels of animosity or social tension between social groups. In either case, it would serve a water manager well to be aware of the range and degree of tensions (legal, political and social) in the system: if the institutional capacity increase does not directly or indirectly address these tensions, it may stand a poor chance of reducing conflict.

6.1.3 … Additional conclusions on the limitations of a banking system

Even in the case of the successful bank in GWBSIM, the extra institutional capacity did not reduce stress and conflict to zero, suggesting that the banking concept has some limitations in how effective it can be in addressing fundamental (and macro-scale) issues - the variable economic vulnerability of different agents, the effect of hydrologic variation on the stress in the system, and so on. The fact that the bank was most beneficial to those agents who could take economic advantage of the institution, or those agents who benefited indirectly through its hydrologic effects, suggests that in the longer term it might not be so effective at addressing chronic symptoms of over-allocation. One could argue that in the real Snake, conflict is emerging through strongly economic drivers: economic interests are being harmed (or perceive themselves as being harmed) by the lack of sufficient water to go around, and so court actions to get other agents to reduce their water use are the most useful tool to address this harm. This ground water bank does not reduce demand: it might even increase demand over time as agents perceive more availability and increase production. This is not demonstrated by the model, but is a possible forecast for a banking future.

6.1.4 … Conclusions on contributions to the Basins-At-Risk theory

Aside from addressing the specific hypothesis, what do I have to add to the Basins-At-Risk theory, which correlates increased institutional capacity with reduced water conflict? First, it is clear that the theory is not watertight. There exist potential systems where simply adding institutional capacity will not, on its own, address water conflict. For example, where the institution requires a degree of equity in participation (i.e. all stakeholders get an equal chance to participate in the institution and collect benefits from it), pre-existing economic and political conditions may mitigate against that equity. For this reason, it may be necessary in some instances to increase the strength and frequency of government intervention. Conversely, expanding institutional capacity without addressing how the new capacity is received by stakeholders can ultimately result in failure to address conflict, even if the institution has considerable environmental and/or economic benefits. The balance between economic carrot and government stick can be critical to avoid either stifling the institution's effectiveness, or letting it run wild without guidance and control. In summary, we can add the following caveat to the overall body of theory:

Addendum 1: Pre-existing political and economic conditions may lead to inequities and inefficiencies and result in failure of increased institutional capacity to mitigate water conflict.

The simulations also showed the importance of individual perspectives on a proposed institution. While 'emotional' variables are rarely a part of any engineering or policy assessment, nevertheless they do play a certain role in the reception of an institution by a stakeholder community, and its continued success or failure. GWBSIM and AlbAgent incorporated detailed emotional characteristics, parameterized on very limited empirical grounds. The choice of which emotional variables to include, however, was based on the in-depth interviews conducted in Idaho, and discussions with regional experts in Spain. So, while the validity of the exact emotional states of agents in both GWBSIM and AlbAgent is somewhat suspect and not appropriate to use in a predictive manner, the models are useful for illustrating the potential power of emotional and other internal cognitive variables on the overall success of an institution. We can add to the theory the following:

Addendum 2: The success of an institution in mitigating conflict may be partly dependent on individual perspectives of the stakeholder population, particularly cognitive dimensions such as emotions and degrees of inter-stakeholder communication/cooperation.

The modeling results suggest the possibility that increasing institutional capacity can in fact increase the environmental sustainability of a system without necessarily reducing conflict in that system, and vice versa. From AlbAgent's results it is clear that the banking system contributed a large volume of water to aquifer recharge that would otherwise not have been present. However, this did not address social conflict, and in a real system such conflict might lead to the failure of the institution and its removal and/or replacement. In the case of GWBSIM, the institution succeeded in reducing conflict but probably did not make a substantial contribution to the environmental sustainability of irrigated agriculture. While longer term outcomes for GWBSIM were not simulated, it could be hypothesized that without substantial environmental benefits, in time the institution would have failed. In other words, institutional capacity needs to be effective at addressing the multiple potential roots of conflict. This is an argument for holistic solutions that address environmental, economic and political problems. Given that one institution is unlikely to be able to achieve this on its own, this suggests that a suite of new institutions may be necessary in a given setting to address the multi-faceted nature of water conflict. Few systems have simple problems, and so I would go so far as to suggest that this a requirement when thinking about institutional solutions to water conflict. Consequently, we can add the following to the theory:

Addendum 3: Adding institutional capacity may not reduce conflict, and may in fact increase conflict, if it does not address the multiple potential roots of conflict in society and environment.

From my discussion of model results, I can suggest some modifications to the theories of change for both settings which I advanced in the major hypothesis. Previously I suggested that the eastern Idaho setting was institutionally frozen, whereas the eastern Spain setting had two institutional systems coexisting - local and regional/national scale - with variable levels of 'freezing' between the systems. The implication of an institutionally-frozen setting is that change is generally more dramatic, because continuous, gentler change is not possible in the face of institutional inertia. Both models implicitly tested this by simulating both non-change and change scenarios; the results show that a period of institutional equilibration may be encountered after the introduction of change. Examining changes in both internal cognitive, external environmental and even external social variables suggests that zero change scenarios have lower 'equilibration' peaks than the change scenarios. I briefly discussed earlier the inherent equilibration period resulting from the nature of simulation modeling and the mismatch between parameterization and the stable system state, but even including this assumption, the change scenarios experience a much steeper re-adjustment across most system variables. The implication for BAR theory is as follows: introducing new institutional capacity will likely result in a significant re-equilibration of the social and economic system. The severity of this adjustment will have implications for the later success or failure of the institution, since the system will take a time period to return to normal proportional to the initial peaks or troughs in system variables. These results are also an argument for extended testing of new institutions, upwards of a decade for particularly large and complex changes. Expecting dramatic results for systems that implicate environmental systems (which are usually slow to respond to physical change instituted by human action) may lead to disappointment and weakening of the institution. We can add the following to the theory:

Addendum 4: Institutional capacity will perturb the system to which it is added. The later success or failure of the institution in mitigating conflict may depend on the size of this initial perturbation.

Finally, the simulations have underlined the importance of transaction costs and administrative dynamics to the fate of new institutional capacity. Most new institutions, whether as complex as a standalone aquifer banking system, or simply new regulations for regulating some component of water use, will add some amount to the transaction costs facing stakeholders, and change the temporal organization of actor behavior. Getting the administrative structure of the institution right is critical to making these added costs as small as possible, and avoiding new damaging feedbacks as a result of the new timetable. GWBSIM's banking system encountered damaging imbalances between deposits and leases partly because of the enforced delay in allowing leases after the bank was instituted. AlbAgent's banking system introduced interesting and not entirely useful cycles of activity in the wider model by restricting participation to one transaction a year and not staggering applications across each year. The cycle of application, approval, and notification in both models undoubtedly added cognitive overhead to each agent, and kept the government agent extremely busy. One could imagine a much more streamlined approach, perhaps testing an 'honor' system where transactions would be free of administration within certain volume limits. We can add the following to our theory:

Addendum 5: The administrative costs and time dynamics of a new institution can have both positive and negative effects on agent behavior that may impact the effectiveness of the institution in reducing conflict. Institutional design from the perspective of minimizing transaction costs for stakeholders, and adjusting the new institution to existing economic and political action cycles, may have important implications for overall institutional success.

6.2 ... Research Question 2

Question 2: What do the significant institutional differences between the western US and eastern Spain mean for an attempt to build a more generic agent architecture (cognition and action mechanisms) that could be used to simulate socio-hydrologic systems across political, geographic and cultural borders?

With these two models I have attempted to show that it is possible to transfer the same concepts of agent cognitive architecture between very different institutional and cultural settings, and still obtain reasonably credible and workable results. However, confirming this hypothesis required some creative interpretation of 'generic' and 'universal', limiting these terms to the conceptual model being adopted and not the detail of the technical implementation. My experience in developing the different agent typologies for each model suggests that developing a *truly* universal socio-hydrologic agent, where the complete technical implementation of the agent (cognition and action) is transferred wholesale from one model to another, is not possible. This is particularly true for the action mechanisms that agents must be equipped with. The original intent with the GWBSIM to AlbAgent transition was to port the existing set of actions in GWBSIM straight into AlbAgent. However, desired improvements in efficiency and effectiveness of the agent architecture, parameterization changes appropriate to locale which necessitated background architectural changes, and completely new components required for the new setting, meant that agents in GWBSIM and agents in AlbAgent have significantly different actions in terms of both technical implementation and technical description. At this point I suggest the following addenda to the hypothesis:

1. A universal socio-hydrologic agent is entirely possible, but only from the perspective of the framework of the agent's cognitive architecture. I define 'cognitive architecture' in this instance as the theory that underlies the way the agents in the model make decisions. The BDI approach adopted in these models appears to work well, and provide great flexibility for changing real world settings: the beliefs, tangible resources, desires and even intentions may all change, but the basic structure is unaffected.

2. A universal socio-hydrologic agent is not possible if that definition requires a complete technical implementation that can be implemented 'as-is' in new models, perhaps as a portable code library. Most settings, even restricting ourselves to the United States, are sufficiently different in terms of actors, environments, institutions and range of possible actions by actors in their environment, that the technical differences in parameterization will require unavoidable new coding in significant amounts on top of any standard library. If the basic skeleton of a socio-hydrologic agent is sought rather than a complete implementation, universal portability and utility might be more achievable. The series of figures in Appendix B lays out my personal vision for what the ideal socio-hydrologic agent skeleton would include. The vision is organized along hierarchical lines, with expansions for detail at each sub-component of the overall cognitive control in each agent. Communication between agents is also addressed. This set of diagrams is offered as a potential blueprint for a generic hydrologic agent framework that does not specify the technical implementation. By making this kind of framework available to new modeling teams, it might be possible to reduce the normally laborious task of identifying the appropriate cognitive architecture most relevant to a socio-hydrologic modeling exercise. The work completed for this thesis does not completely shut the door on a universal socio-hydrologic agent in both conceptual and technical implementation, but the design and implementation of this agent would have to include an enormous library of plug-and-play components. This is the kind of project suited to a community effort, with successive implementations of socio-hydrologic agents leading to successive improvements in the range of functionality supported by the agent code, and the robustness of its implementation.

3. The modeling results suggest that the challenge in developing portable socio-hydrologic agents may not extend to institutional mechanisms. Evidence of this is that the ground water bank in GWBSIM was essentially directly ported to the AlbAgent setting with only minor technical changes. It was, instead, at the level of the Farmer agent in AlbAgent that major institutionally-related changes had to be made to cognition and action. Farmer agents in the Spanish setting had far less political and economic independence relative to the equivalent agents in Idaho, for example. Farmer response to government action, and anticipation of the same, also varied considerably between the two settings. Consequently, differences in the way agents perceived institutions, rather than the structure of the institutions themselves, were the principal motivations for changing agent architectures between the two models.

7.0 ... Suggestions for Further Work

My experience in designing, developing and running two large and complex agent-based simulation models suggests to me several key and under-served research areas pertinent to advancing the theory and practice of agent-based modeling, specifically agent-based modeling of socio-hydrologic systems. I discuss these areas below. My focus on a hypothesis relating institutional capacity and water conflict has also made clear some major deficiencies with existing theory and potential avenues for future work using simulation modeling. These avenues are also discussed below.

7.1 ... Agent-based modeling of socio-hydrologic systems

The first important point is that the cognitive architectures of socio-hydrologic agents do bear some distinctive traits relative to other applications of agent-based models and the agent concept. For example, socio-hydrologic agents have close and dynamic relations with their physical environment, and so the engineering of these relations requires special care relative to other applications of agent modeling. Furthermore, there may be unique dimensions of the social system that socio-hydrologic agents need to be able to handle (such as water conflict and institutional mechanisms), for which specific agent logic will be needed and which precedent in other fields of application will not shed much light on. However, the very concept of socio-hydrologic agent remains unknown in the literature, and little explored by most researchers. I have attempted to show in this thesis that some degree of universality in cognitive architecture is possible, i.e. that different water resources management settings can use agents with the same basic decision making framework. However, I have also shown that agent-based models in different settings may require significantly different technical implementations depending on the social and environmental qualities of the setting. This suggests that there is potentially fruitful work in exploring to what extent the need to tailor technical implementations could be avoided by improving the efficiency and adaptability of agent algorithms. The goal of such work should not just be to make available more robust and portable agent libraries, but to build theory related to just what defines a socio-hydrologic agent. I have offered a start on this endeavor with the framework diagrams included in the appendix, part B. My strong feeling is that such work should proceed collaboratively and through open source tools (e.g. code repositories and development foundations), since the experience of any one modeler is overshadowed by the collective intelligence of the agent-based modeling community.

7.2 ... Institutional capacity and water conflict

The simulations and results I have described in this thesis have hopefully shown that there are indeed strong dynamics relating institutional capacity and water conflict, and that the BAR theory (increasing institutional capacity will reduce water conflict) is sound in so far as it implies institutional capacity and conflict are connected. However, the results from the two models have also shown that the BAR hypothesis may not always hold true, and that some modifications to the theory may be necessary. There is considerable further work to be done ascertaining exactly what predisposes a system to experience a certain institutional/conflictual dynamic. Simulation models have an important role to play in this effort, since it is only through complex simulation modeling can we ever hope to have the kind of social laboratory needed to test alternative theories relating institutions and conflict. Future work could include: more exhaustive testing of existing models to see whether it is variation in agent internal cognition or the external environment that is most responsible for generating and prolonging conflict; implementation and testing of alternate institutions to see what role form (as opposed to size) of institutional capacity plays in conflict dynamics; and whether it is possible to develop probabilistic descriptors allowing decision makers to access the risk of increasing conflict in a system when implementing a new institution or adding extra institutional capacity.

7.3 ... Ground water banking

The ground water banking institution was the central focus of both models. The basic specification of the institution referenced work by Bryce Contor, hydrologist from IWRRI in Idaho Falls, ID. This specification was made in light of the existing limitations in the legal and political scene surrounding water in Idaho, and consequently assumed that the system would only be open to the least radical version of ground water banking possible. This conservative version of banking is by no means the only one, and there is a great deal of further work that could be done to explore, through simulation modeling, the implications of changing a variety of institutional variables. These include: the means by which the price per unit water is set (which could have implications for the balance and efficiency of the bank); the means by which agents are encouraged to lease and/or deposit (which could address some of the potential transaction imbalance issues this thesis identified); the diversity and scale of bank participation (should all agents participate, or perhaps only selected typologies?); whether the physical means by which leases and deposits are actuated matters to the overall operation of the bank; and whether social and environmental differences between settings (even within one country) affect the design of a ground water bank. Once again, agent-based simulation modeling can be a powerful tool in answering these questions, since it allows rigorous and transparent testing of theories that would otherwise rely on studies of real systems that either do not yet exist or for which suitable performance data do not exist.

Appendix

Part A

Semi-structured interviewing guide – eastern Idaho, January/February 2007

Not for circulation

Introduction:

- *The purpose of the interviewing*: to develop a description of how the many individuals and agencies make decisions about management and the use of surface and groundwater in the Eastern Snake; to understand the many perspectives on how the river and water delivery systems work; to explore general opinions on the potential for ground water banking.
- *The nature and intent of the modeling*: build an integrated social-biophysical model of the water resource systems in the Eastern Snake River Plain, providing a credible and realistic tool for simulating the social, economic and environmental response of the region to different ground water banking scenarios.

Theme 1:

The Big Picture: explores the most salient issues locally and regionally for the stakeholder.

1.1. From a general perspective, what are the biggest problems or issues related to water use and management in the Eastern Snake, at the present time?

1.2. What are the core economic factors affecting these issues?

1.3. Are there any major problems or issues related to water use or management in the Idaho Falls area that are not seen on a more regional scale?

1.4. Do you see any intersection between economic and natural factors?

1.5. How closely is the economic future of the urban areas in the Snake tied to the agro-economy?

Theme 2:

Decision-making: the typical decisions facing a stakeholder during each year

2.1. What are the producer decisions each year that are most influenced by economic factors, and what are those factors?

2.2. Do any of these decisions have ripple effects in the wider producer community, or are any decisions particularly contentious for any reason?

2.3. Are there any producer decisions particularly susceptible to intervening economic factors that might act to render them ineffective after they've been made (and an action taken)?

2.4. Where are the principal areas of uncertainty in the economic factors that influence producer decision-making?

2.5. How do you see farmers handling this uncertainty?

2.6. What level of control do farmers have over their economic conditions?

2.7. What is the typical level of understanding of producers as to the micro- and macro-scale conditions within which they operate?

Theme 3:

Others: the influence of the decisions and actions of other individuals and institutions

3.1. From this list of stakeholders, please describe for each stakeholder what you see as their economic role in the Eastern Snake, if they have one.

3.2. Please pick out the stakeholders whose opinions and views tend to have the strongest economic influence over other stakeholders.

3.3. Which of these stakeholder tend to conflict economically the most, and why?

3.4. Which of these stakeholders tend to collaborate the most, and why?

3.5. Is it possible to identify a trend toward economic conflict or collaboration among stakeholders at the present time?

3.6. Are there economic factors, processes or activities in different areas of the plain that interfere with each other – not necessarily in direct conflict, but perhaps in competition or somehow linked so as to influence each other strongly?

Theme 4:

Interests: the principal stake that the individual or organization has in the management of the Snake's water

4.1. Are producers largely satisfied – from an economic perspective – with the current arrangements for managing water?

4.2. If there are areas of dissatisfaction, what do you think the typical producer would like to change to orient the economic system more toward their interests?

4.3. Are there legal or institutional links to the economic system that we haven't talked about so far?

4.4. Is there scope for changes to the legal or institutional system that would improve economic conditions for producers?

Theme 5:

Future vision: where water use and management is headed

5.1. What do you see as the future of water use and management in the Eastern Snake?

5.2. What do you think will be the major economic factors and trends in the future?

5.3. What would you like the future to be?

Theme 6:

Ground water banking: economics and options for banking

6.1. From an economic perspective, do you have any opinion on how useful ground water banking might be in the Eastern Snake?

6.2. Ground water banking would likely have impacts on the local and regional economic system if implemented. Are there any particular factors, processes or issues that you'd like to see explored using simulation scenarios?

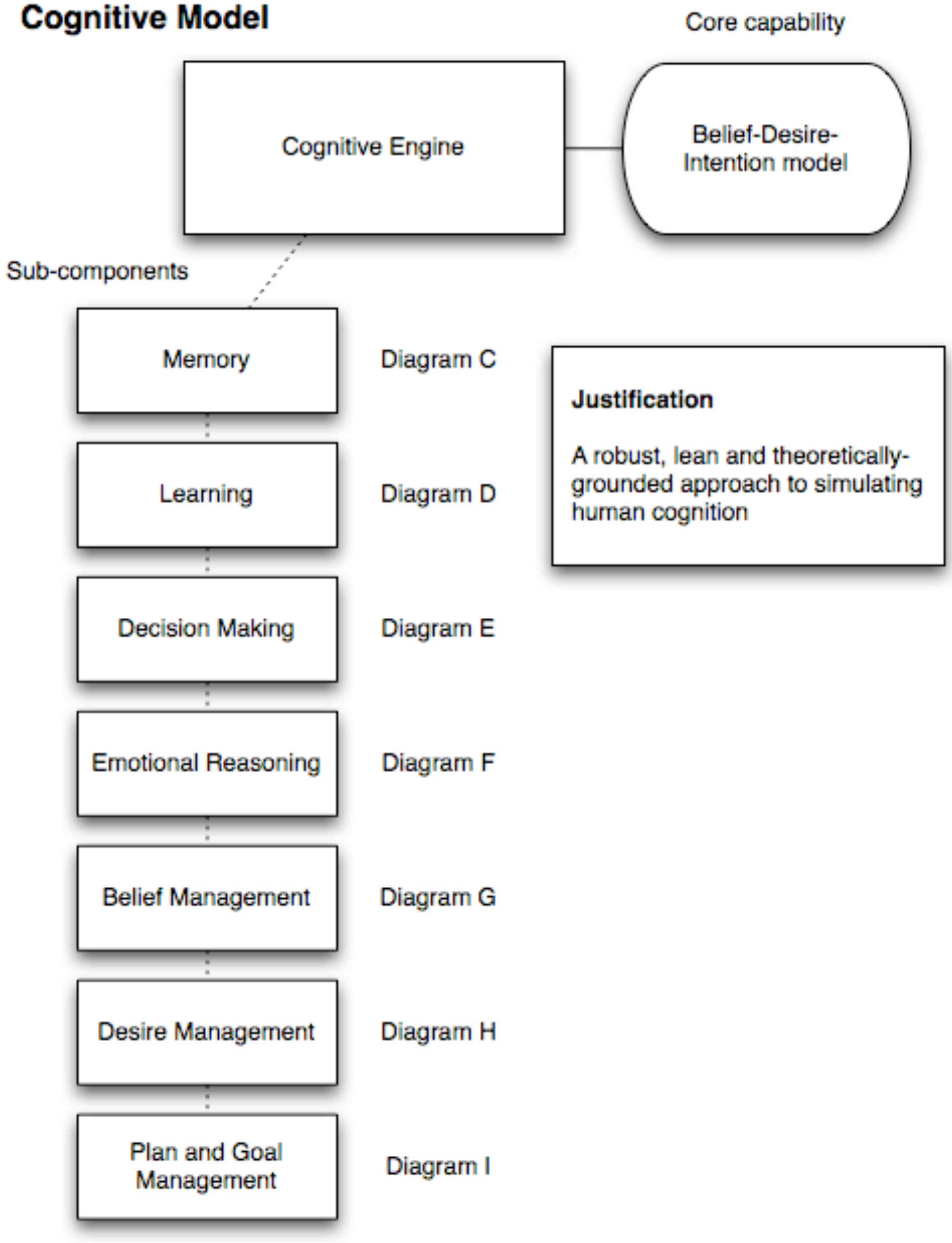
Part B

Generic hydrologic agent: proposed framework for adaptation to and implementation in specific simulation contexts

Note on diagrams

The sequence begins with an overview of the cognitive architecture of the ideal hydrologic agent. The most senior component is the cognitive engine, which provides the functional code that knits together all the various sub-components. This may take the form of a higher level state chart, controlling transitions from one deliberative process to another; or it may take the form of a more dynamic continuous loop, accessing sub-components as needed. The Belief-Desire-Intention model of cognition is recommended over ACT-SOAR, or other more complex cognitive models, for its relative efficiency and ease of implementation. The seven sub-components are not necessarily organized in an optimal fashion, and an implementation might find that there are overlaps between sub-components that require some merging of categories. They are merely offered as a suggested map of cognitive elements that should, ideally, be part of an agent's cognitive architecture. Each sub-component is outlined in detail in the relevant diagram: capabilities of each sub-component and a brief justification for the capabilities are offered.

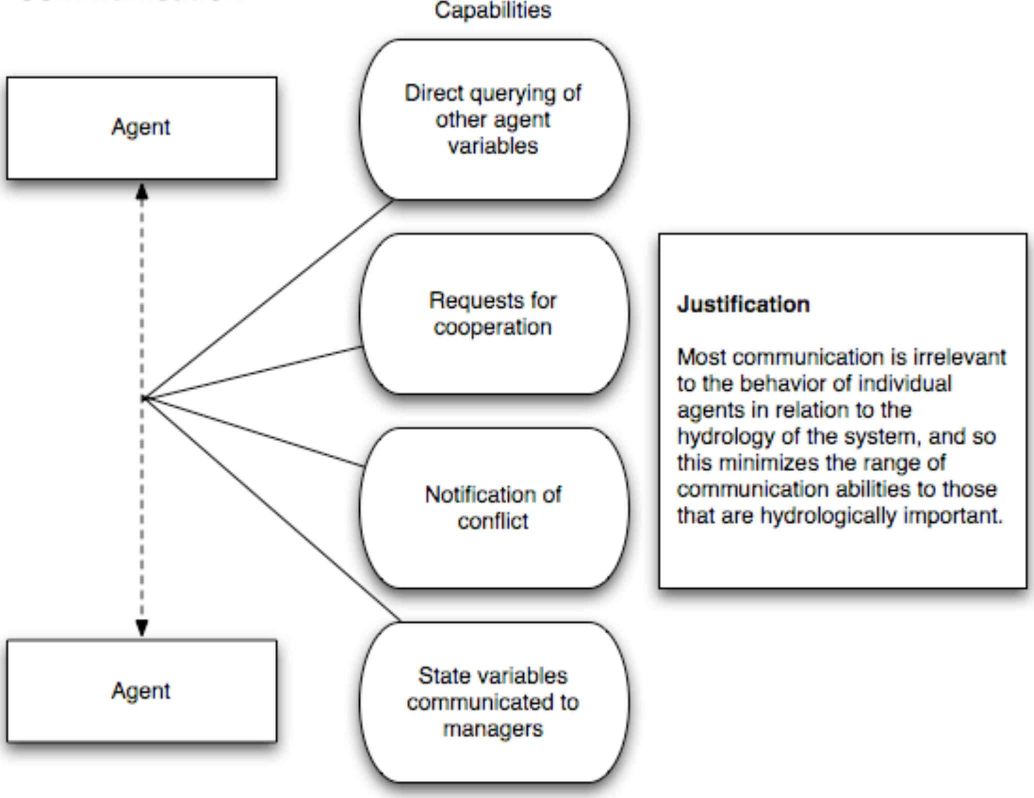
Diagram A:
Cognitive Model



Justification

A robust, lean and theoretically-grounded approach to simulating human cognition

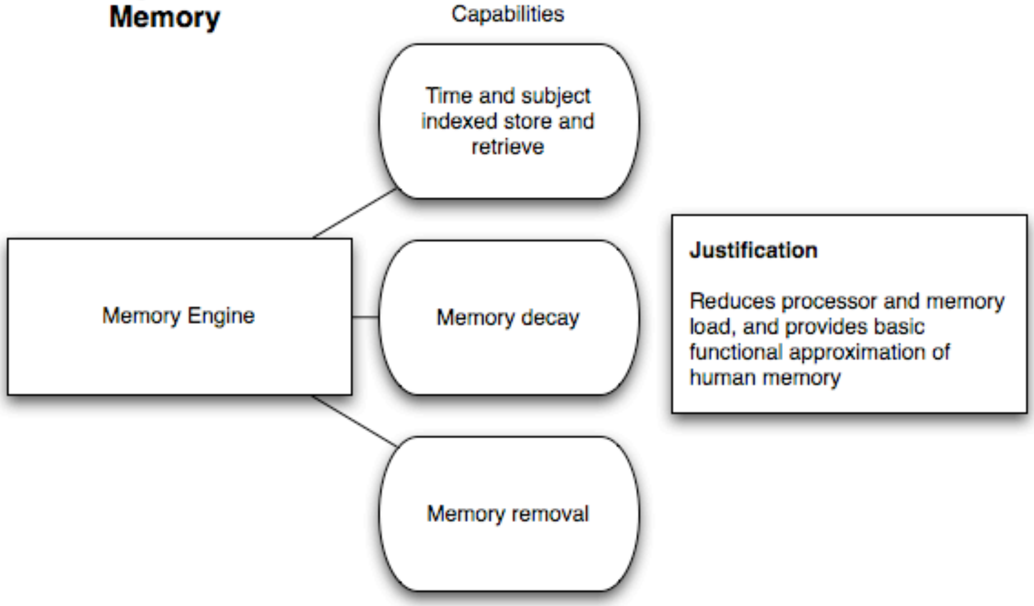
**Diagram B:
Communication**



Justification

Most communication is irrelevant to the behavior of individual agents in relation to the hydrology of the system, and so this minimizes the range of communication abilities to those that are hydrologically important.

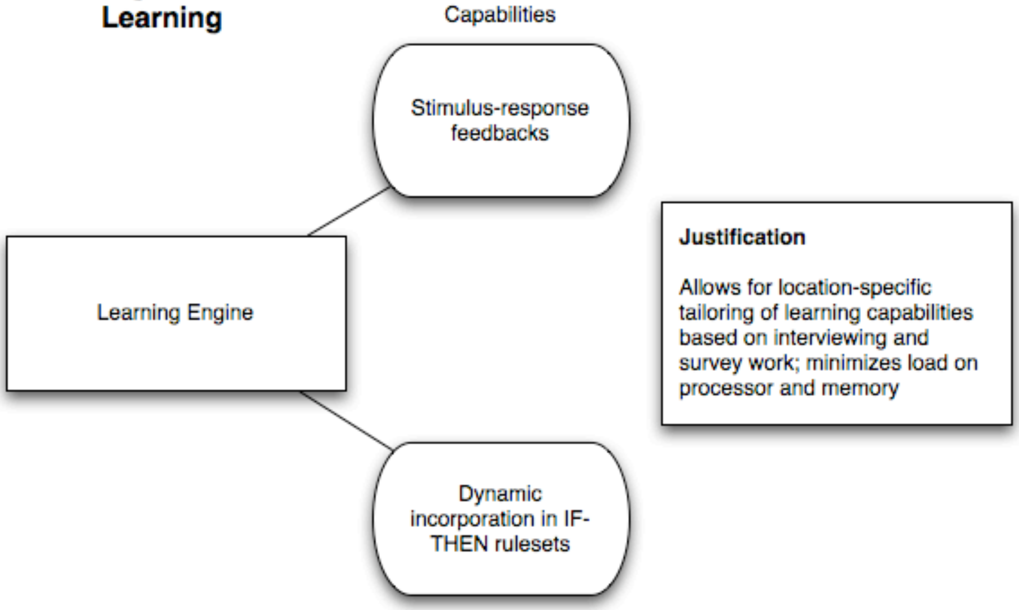
**Diagram C:
Memory**



Justification

Reduces processor and memory load, and provides basic functional approximation of human memory

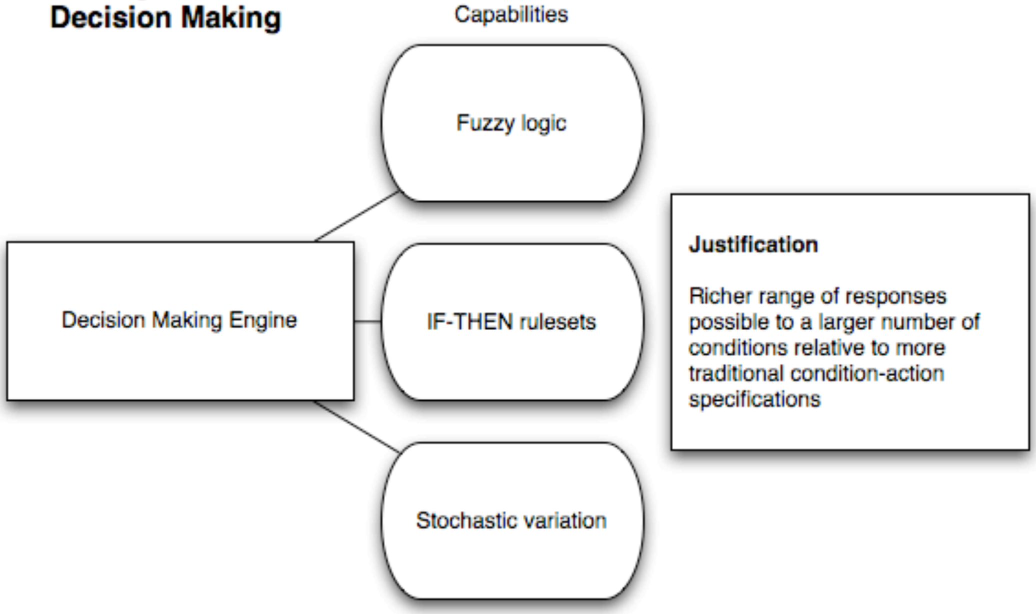
Diagram D: Learning



Justification

Allows for location-specific tailoring of learning capabilities based on interviewing and survey work; minimizes load on processor and memory

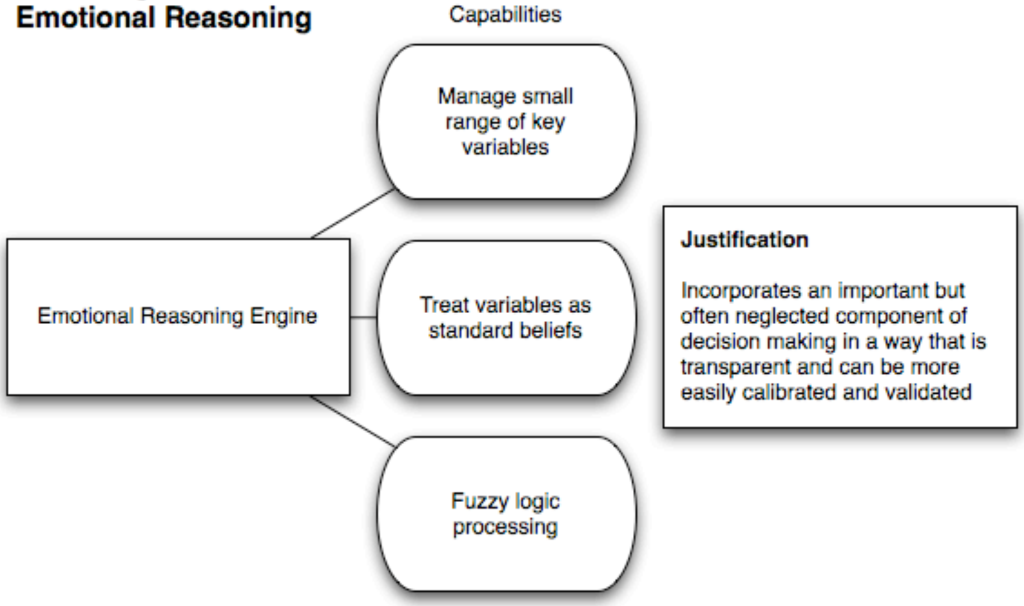
Diagram E: Decision Making



Justification

Richer range of responses possible to a larger number of conditions relative to more traditional condition-action specifications

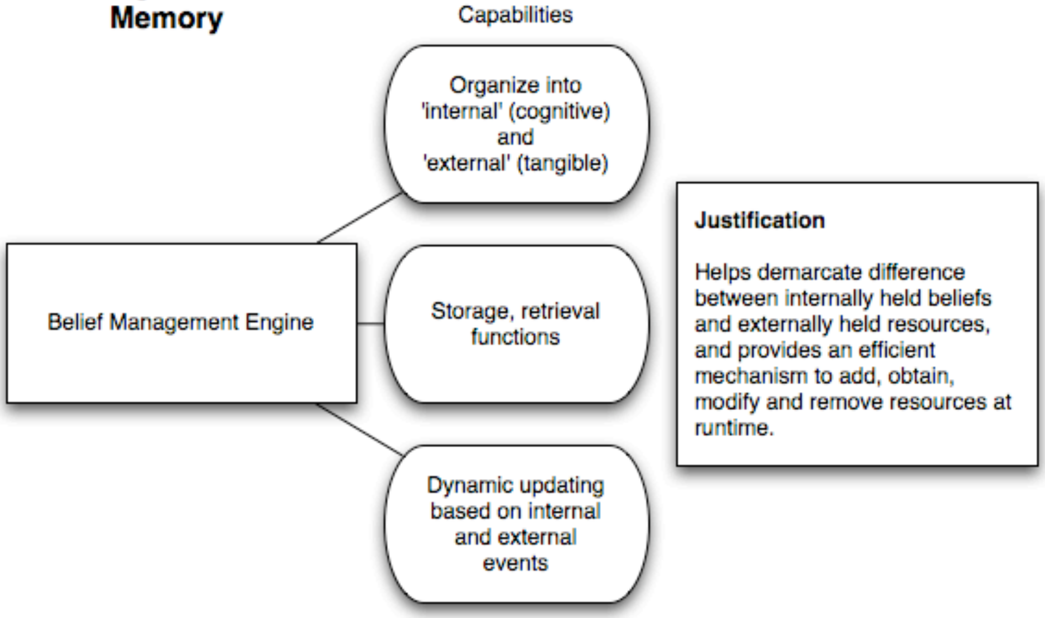
**Diagram F:
Emotional Reasoning**



Justification

Incorporates an important but often neglected component of decision making in a way that is transparent and can be more easily calibrated and validated

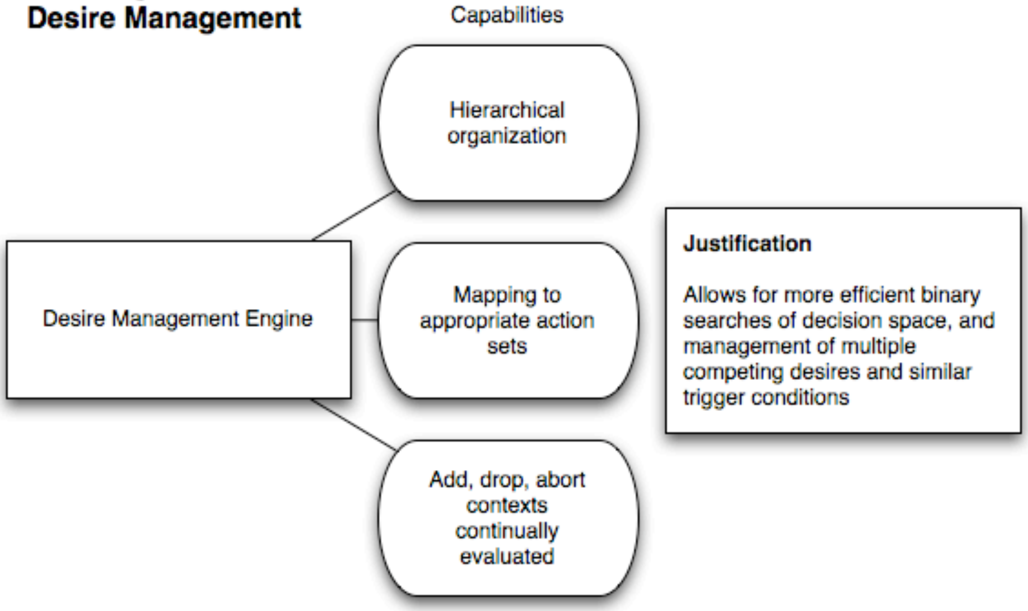
**Diagram G:
Memory**



Justification

Helps demarcate difference between internally held beliefs and externally held resources, and provides an efficient mechanism to add, obtain, modify and remove resources at runtime.

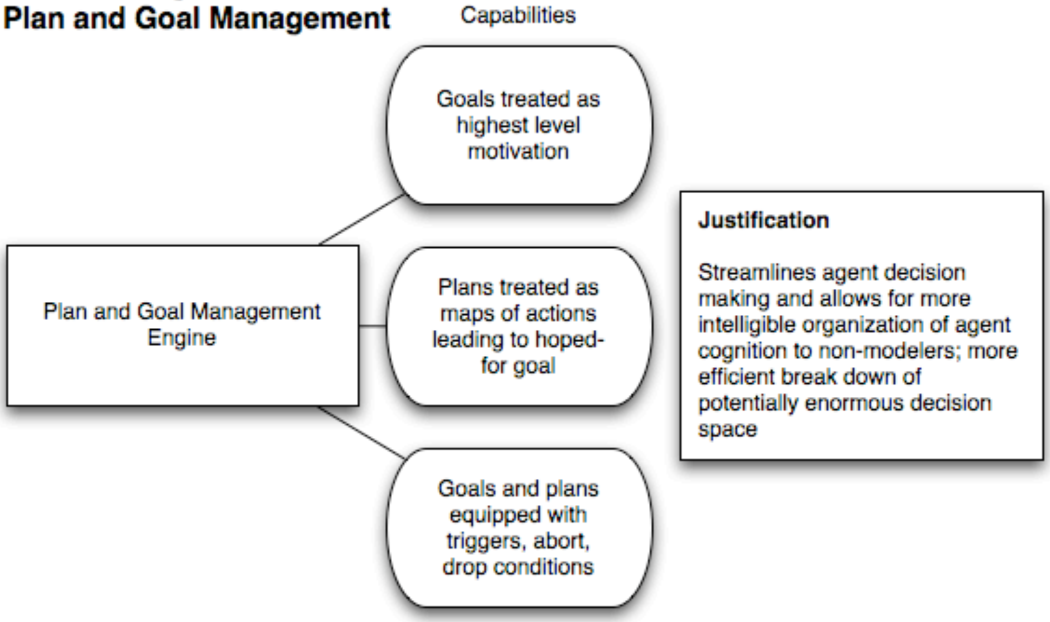
Diagram H:
Desire Management



Justification

Allows for more efficient binary searches of decision space, and management of multiple competing desires and similar trigger conditions

Diagram I:
Plan and Goal Management



Justification

Streamlines agent decision making and allows for more intelligible organization of agent cognition to non-modelers; more efficient break down of potentially enormous decision space

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