Global Water Games: A Participatory, Agent-Based Modeling Platform for Watershed System Management

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Abstract

Watershed system management is becoming an increasingly important problem in the face of continuing growth in population, economic activity, and agricultural production worldwide. Watershed systems provide human society with numerous critical economic and ecosystem services. But effective management of watershed systems can be extremely difficult. Watershed systems are not simple systems—they are complex socio-ecological systems with many stakeholders who often have diverse and often competing interests. To facilitate effective watershed system management, decision makers around the world need better tools to help them explore the vast array of policy options available to them and build consensus among different types of stakeholders.

The UVa Bay Game® is a multidisciplinary attempt to address these myriad and complex management challenges for the Chesapeake Bay Watershed. It applies a spatially explicit, agent-based, participatory simulation framework to modeling the Chesapeake Bay Watershed, presented in a “serious game” format. Its validated modeling approach brings together local decision makers and a variety of Watershed stakeholders, enabling them to explore the effects of different policy choices and learn about the systemic nature of the challenges facing the Chesapeake Bay Watershed.

This thesis presents the Global Water Games platform—a general, participatory, agent-based modeling framework for watershed system management. It expands and generalizes the modeling approach of the UVa Bay Game®, making it flexible enough to adapt to a variety of watershed stakeholder needs and objectives. The reusable and extensible Global Water Games platform allows modelers and stakeholders to build similar participatory, agent-based watershed simulation “games” for any watershed system around the world, provided basic input data is available. Models built using the Global Water Games platform support effective watershed system management through the dual purposes of providing policy decision support and facilitating social learning among watershed system stakeholders.

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AD — Agent decisions

AV — Agent variable

EX — Exogenous factors

HT — Historical trend

NF — Natural forces

SV — Spatial variable

t — Current time step

UE — Upstream effects

1. Introduction

1.1 Background on Watershed System Management

The need for effective management of watershed systems has never been greater. As both human populations and our economies continue to grow, our reliance on secure, robust supplies of clean water—a service many take for granted—only becomes more critical. A "watershed" is defined as the geographical extent of land whose water runoff all drains to a single location, such as the large swathe of the US Mid-Atlantic region that ultimately drains into the Chesapeake Bay. A "watershed system," on the other hand, is the dynamic, interacting combination of a natural watershed and the elements of human society that call the watershed home. They are socio-ecological examples of *complex systems*—systems made up of numerous independent elements, in which the macro-level system behavior *emerges* from the micro-level interactions the elements have with one another and with their environment [1]. Complex systems can often behave in ways that are unexpected or even counterintuitive to humans. One cannot gain insight into the global-level operation and behavior of a complex system by understanding its elements individually; the system must be analyzed in a holistic way [1].

Watershed systems offer critical economic services to their human inhabitants, both directly in the form of an ongoing, renewable supply of fresh, clean water, and indirectly, by providing support for agriculture, shipping, recreation, and many other economic activities linked to the water [2]. They also provide "ecosystem services," defined as benefits nature provides to humans for free, such as water purification, waste assimilation, storm buffer zones in the form of coastal wetlands, supporting populations of fish and other aquatic flora and fauna, etc. [2]. "Watershed system management" is the deliberate and coordinated implementation of policies—or lack thereof—by decision makers and stakeholders in the watershed designed to achieve one or more macro-level outcomes in a complex socio-ecological watershed system. Target system-level outcomes for a watershed system management strategy might include maintaining a sufficient overall quantity of water supply, while keeping certain water quality metrics within acceptable ranges, to ensure that the watershed system can sustainably provide a satisfactory level of economic and ecosystem services for human and environmental needs.

Effective watershed system management can be devilishly difficult. Complex systems, including socio-ecological watershed systems, often prove impervious to deep understanding via traditional reductionist scientific and engineering methods that focus on their individual elements in isolation [3]. Despite policy makers' desire for simple, universal policy solutions, "panaceas" that focus on only one aspect of a socio-ecological problem are unlikely to be successful [4]. Writing fifteen years ago, Holling, et al encapsulate the issue in this way, which still holds just as true today:

> "The answers are not simple because we have just begun to develop the concepts, technology and methods that can address the generic nature of the problems. Characteristically, these problems tend to be systems problems, where aspects of behavior are complex and unpredictable and where causes, while at times simple (when finally understood), are always multiple. They are non-linear in nature, cross-scale in time and in space, and have an evolutionary character. This is true for both natural and social systems. In fact, they are one system, with critical feedbacks across temporal and spatial scales. […] Furthermore, understanding

> (but not necessarily complete explanation) of the combined system of humans and nature is needed to formulate policies." [5]

Further complicating the effort to implement effective watershed system management policies are the facts that watershed systems tend to be split across multiple different political or administrative regions, and that different stakeholder groups within the system often have competing or conflicting interests [2]. Comprehensive solutions to such problems are not likely to be simple. They are likely to be multi-faceted, multi-scale, and time sensitive themselves, balance the needs and interests of many diverse stakeholders, and may have unforeseen side effects [4].

1.2 The Need for Effective Watershed System Management

Despite the difficulty involved, the consequences of poor or nonexistent watershed system management can be dire. In recent years, watershed systems have come under increasing stress due to a number of ongoing trends: population growth, increasing industrial and agricultural demand for water, continuing urban and exurban land development, climate change, and many others. Their ability to sustainably provide an adequate water supply of acceptable quality to meet human and ecological needs has been called into question. Two of the risks posed by a lack of effective watershed system management are persistent water quality degradation and systemic imbalance between water demand and water supply, leading to chronic water shortages. These risks are exemplified by the cases of the Chesapeake Bay in the United States and the Aral Sea in Central Asia, respectively, over the past half-century.

1.2.1 Chesapeake Bay Watershed

The Chesapeake Bay is deeply embedded in the history and culture of the United States. It also happens to command a major watershed on the US East Coast. Its watershed system encompasses approximately 64,000 square miles and currently supports a population of over 17 million people, which has more than doubled since 1950 [2]. The Chesapeake Bay watershed stretches from Virginia to New York, containing parts of six US states plus the District of Columbia [2].

Throughout the first part of the twentieth century, population growth, increasing agricultural activity, and continuing urban development in the Chesapeake Bay's watershed steadily degraded the health of the Bay ecosystem, according to the Chesapeake Bay Foundation (CBF)'s Bay health index [6]. The CBF Bay health index is a composite metric based on thirteen diverse indicators of the Bay ecosystem's condition. These include water quality metrics, such as nitrogen and phosphorus loads, dissolved oxygen concentration, and toxic contamination, as well as the health of selected populations of aquatic plant and animal life that call the Bay home, and so on [6]. Excessive nitrogen and phosphorus loads in the Bay's water—primarily caused directly or indirectly by human activity, such as runoff from agricultural, urban, and suburban land, and industrial and municipal point sources in the Bay's watershed—are of particular concern [7]. Nitrogen and phosphorus are nutrients that encourage plant growth, just as in terrestrial fertilizers, and abnormally high levels of these nutrients in the Bay's waters cause large algal blooms each spring [2, 8]. When these algae die, they sink and decay, a process that consumes dissolved oxygen in the water [2, 8]. Combined with the Bay's natural water circulation patterns, this causes deeper waters in some regions of the Bay to become *hypoxic* or *anoxic*—containing little or no dissolved oxygen in the water, respectively—each summer [2, 8]. Aquatic animals require certain minimum levels of dissolved oxygen in water to live, so hypoxic or anoxic regions create “dead zones” in which few or no animals can survive [2, 8]. The concentration of dissolved oxygen and the size of the anoxic region are commonly followed indicators of Bay health, as seen in Figure 1 [2, 8]. Decisions made by human stakeholders at multiple levels in the watershed system, from state and federal policy makers down to individual farmers and land developers, can interact and work their way through the system’s complex, interdependent mechanisms, causing the system-level emergence of dead zones in the Bay—and many of these stakeholders are not even aware they are integral parts of the Chesapeake Bay Watershed [2]!

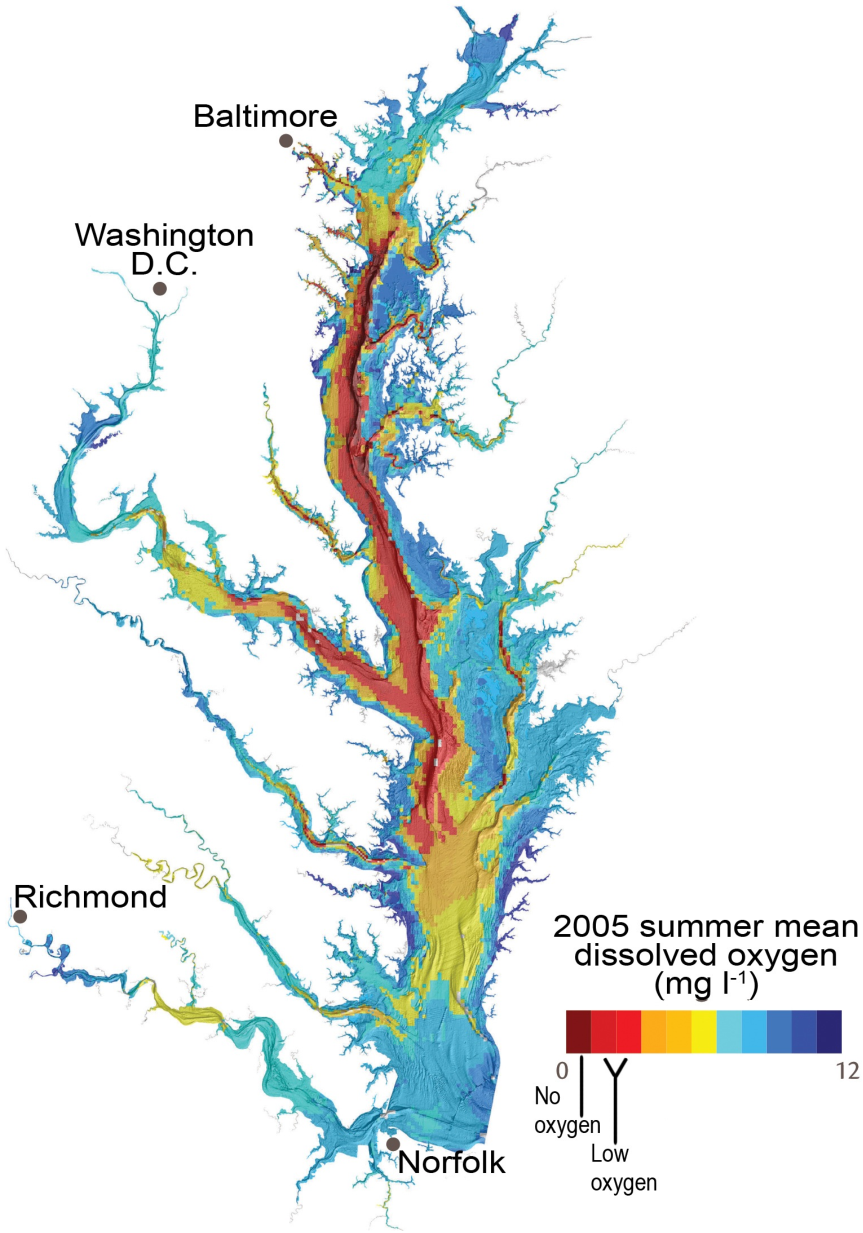


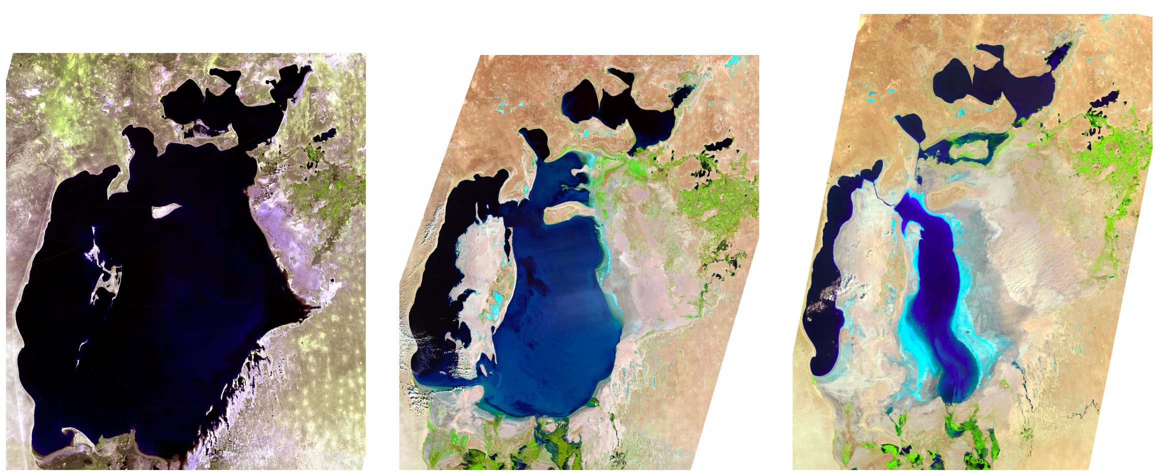
Figure 1. A map of mean dissolved oxygen concentration in the Chesapeake Bay during the summer of 2005. Darker shades of red indicate the hypoxic and anoxic dead zones in which few or no animals can survive. Image credit Wicks, et al [8].

With responsibility for the Chesapeake Bay watershed split between multiple political jurisdictions, and no coherent and coordinated watershed system management strategy in place, the ecological degradation of the Bay continued unabated throughout much of the twentieth century [6]. The situation reached a nadir in 1983, when the CBF Bay health index hit a value of 23 on a 0-100 scale (with 100 representing a pristine Bay ecosystem) [9]. By the year 2000, the oyster population in the Bay had collapsed to about 2 percent of its original size, and underwater grass beds, a critical habitat for blue crabs, had been reduced to just 12 percent of their historic levels [10]. The blue crab population itself was stressed to the point of destabilization by the dual pressures of overfishing and habitat loss [10]. With a Bay health index score still languishing in the 20s, the Chesapeake Bay Foundation described the Bay as a "system dangerously out of balance" [10].

The problem of abnormally large algal blooms, caused by artificially elevated nutrient levels, resulting in hypoxic or anoxic dead zones—and the ecological costs that accompany them—is not limited to the Chesapeake Bay. One 2008 study identifies such dead zones affecting more than 400 watershed systems worldwide [11]. Collectively, these dead zones around the globe can encompass a total area of almost 95,000 square miles, larger than the total area of the United Kingdom [11].

1.2.2 Aral Sea

An even starker and more ominous warning than the ecological woes of the Chesapeake Bay is provided by the case of the Aral Sea in Central Asia—perhaps the most infamous example of watershed system mismanagement in history. The Aral Sea is actually a lake that used to be the fourth-largest in the world [12]. It anchors a massive endorheic basin that, according to some literature, measures as large as 500,000 square miles [13]. Historically, fishing was a vital resource for the towns and villages that dotted its shoreline [14]. The Sea also offered numerous ecosystem services to communities in the surrounding area, such as moderating the region's harsh continental climate and providing habitats for many local species [14]. Beginning in the 1960s, however, policy makers began to divert water from the two main rivers that fed the Sea for agricultural irrigation—policies that, to a greater or lesser degree, have continued to this day [14]. Over the ensuing decades, the demand for water overwhelmed the available supply, and the Aral began to recede. Figure 2 shows the effects in satellite imagery of the Aral Sea and surrounding area taken in 1977, 1998, and 2010. By 2007, the Sea had been reduced to a mere 11% of its historical volume [14].



1977 **1998** **2010**

Figure 2. Satellite imagery shows the Aral Sea and the surrounding area in 1977, 1998, and 2010. Image credit U.S. Geological Survey [13].

As the Sea evaporated, so did the economic and ecosystem services it provided. Local weather patterns began to change—without the moderating effect of the Sea, summers became hotter and winters colder [14]. Dust storms became common, dispersing pollutants that were formerly sequestered in the Sea across thousands of miles, causing widespread illness [12, 14]. Fishing communities that used to be right on the Sea now find themselves up to 60 miles from the new shoreline, devastating their economies [14]. As water evaporates, it leaves any dissolved salts behind; the salinity of the remaining water in the Sea increased by a factor of seven over its historical value—making it twice as salty as the ocean [14]. All but one species of fish in the Sea perished, and many other species of plants, birds, insects, and other animals that depended on the Sea ecosystem also disappeared [14]. During a 2010 visit, the United Nations Secretary-General described the Aral Sea as "clearly one of the worst environmental disasters in the world," adding that he could not see anything except a "cemetery of ships marooned in the sand" of the former seabed [12].

Decision makers responsible for the Aral Sea failed to treat the complex socio-ecological watershed system in a holistic manner. They made the error of trying to maximize just one aspect of it—agricultural production—in isolation from the rest of the system. They did not anticipate or consider possible second- or third-order emergent behaviors in other facets of the system induced by dropping water levels, and what their consequences might be. Their failure to respect the complex, interconnected nature of the broader watershed system resulted in the destruction of every other economic and ecosystem service the Sea had provided.

1.3 A New Approach to Watershed System Management?

It is an economic, ecological, and moral imperative that we, as a society, get better at effectively and sustainably managing watershed systems. We are an integral part of these complex socio-ecological systems, and human action at both the individual and collective levels can have dramatic effects, for good or ill, on the emergent, global-level outcomes of the system. The problem cannot be ignored—the costs of poor or nonexistent watershed system management can be enormous.

Perhaps the single best cause for optimism is the simple fact that decision makers in watersheds around the world have started paying attention to watershed system management, and approaching the problem at a system-wide level. In 1983, in recognition of the cross-border nature of the challenges facing the Chesapeake Bay Watershed, and the common stake all had in the health of the Bay, the governors of Maryland, Virginia, Pennsylvania, the mayor of the District of Columbia, and the administrator of the Environmental Protection Agency signed the Chesapeake Bay Agreement [15]. This landmark accord declared shared responsibility for the management of the Bay between the signatories and committed them to "fully address the extent, complexity, and sources of pollutants entering the Bay" [15]. The agreement was renewed in 1987, and again in 2000 [16, 17]. In 2009, President Barack Obama issued an Executive Order directing the federal government to take the lead in Chesapeake Bay restoration efforts, further recognizing the breadth of the challenges facing the watershed system, and remedies needed [18]. The EPA responded by releasing the most ambitious watershed system management strategy in its history [19]. Policy makers in other major watersheds worldwide have taken their own steps to study or implement watershed management strategies, including in the Colorado River Basin in the southwestern United States, and the Murray-Darling Basin, the primary watershed system in the southeastern Australian interior [20, 21]. Both the Colorado and the Murray-Darling watershed systems face major challenges in water supply sustainability [20, 21].

These well-intentioned initial efforts at comprehensive watershed system management have yielded mixed results. In the case of the Chesapeake Bay Watershed, coordinated preservation and restoration efforts have at least stemmed the continued degradation of the Bay ecosystem [6]. In the period from 1983 to 2012, the CBF Bay health index rose modestly from all-time low point of 23 to 32 (both out of 100), despite a growing population in the watershed system [6, 9]. However, restoration efforts in the past decade have failed to meet the CBF's stated targets and goals by a wide margin [6, 10]. From 2008 to 2012, a period that includes the federal government's new leadership in Bay restoration efforts, the overall health index score improved by only four points—and the CBF still rated the Bay's health as an "F" for four of the thirteen indicators used to create the composite index [6, 9]. The score for nitrogen pollution actually got worse [6, 9]. Perhaps most concerning, the CBF notes that even the modest progress that has been made is threatened by a lack of political consensus about the current watershed management strategy among certain key stakeholders in the watershed system [6].

1.3.1 The UVa Bay Game®

One recent attempt to better understand the inherent complexities of watershed system management for the Chesapeake Bay Watershed is the UVa Bay Game® (or simply "Bay Game"), a collaborative effort involving faculty representing seven different schools within the University of Virginia [22]. The Bay Game is a dynamic simulation model of the Chesapeake Bay Watershed that couples both the human and natural science aspects of the watershed system [2, 22]. It represents the geographical area of the watershed system in a spatially explicit way, breaking it down into seven sub-watersheds, including the watersheds for the Susquehanna, Potomac, Patuxent, Rappahannock, York, and James Rivers, plus the Eastern Shore, that make up the complete Chesapeake Bay Watershed [2]. The Bay Game captures human elements of the watershed system using an *agent-based modeling* approach, representing individual human stakeholders or human-controlled entities, such as regulatory agencies, as individual decision-making *agents* that interact with one another and their environment [22]. The agents represent certain types of real-world stakeholders whose decisions can have an impact on the overall behavior of the watershed system, including farmers, fishermen (crab fishermen known as “watermen” in the Bay), real estate developers, and regulators [22]. The Bay Game also incorporates *participatory simulation*, or allowing stakeholders to participate in the use of the model, by allowing human “players” to interact with a user interface during a “live” run of the simulation model in a “serious game” format [22]. During every Bay Game “game play,” a number of human players participate by taking control of one of the agents in the simulation model, assuming its stakeholder role, such as crop farmer, real estate developer, etc., and making decisions about their livelihood and ecological impact according to their own values [2]. The simulation model focuses on a 20-year period, from the year 2000 to 2020, during which all participants make 10 sets of decisions [2]. The model is initialized at the beginning of each game play with known, published data from the year 2000 [22]. Results from model runs have been compared to real-world data and found to adequately track known key metrics, thus validating the modeling strategy [22].

The UVa Bay Game® has proven a highly useful tool for both informing policy decisions about the Chesapeake Bay Watershed and for fostering awareness and social learning among real watershed stakeholders [22]. The simulation integrates information from the players' decisions and other forces to calculate the health of the Bay ecosystem, the economic status of the agents in the watershed system, and a wide variety of other information, at multiple time steps throughout each game play [2]. It captures how human decision-making at multiple levels can affect both the economic and ecological outcomes of the Chesapeake Bay Watershed system. It can serve as a "laboratory" to explore and test potential policy decisions [22]. Additionally, because it allows real stakeholders to play and re-play the Game, and engage more holistically with the complexities of watershed system management, it can help raise awareness and build consensus about sustainability issues between diverse constituencies in the watershed system [22]. The Bay Game has been played numerous times, including game plays for US Congressional policy makers, corporate executives, and many university and educational groups [23].

The UVa Bay Game® isn't perfect, however. One of its key drawbacks is that it is not "portable" to other watershed systems. After years of development time and effort, it is custom-built to model the Chesapeake Bay Watershed system, its stakeholders, and their specific concerns. In the original Bay Game framework, there is no way to easily and rapidly reconfigure the Game to model additional watershed systems, or different stakeholder objectives and values.

1.4 Problem Statement

The need is clear for better tools to support effective watershed system management in watershed systems around the world. A new way to model watershed systems is needed to help policy makers make sense of the complex problems they are facing, explore the expansive array of policy options available to them, and then formulate effective management strategies. Additionally, the modeling methodology needs to help raise awareness among key system stakeholders about the inherent complexity and interdependent nature of watershed system management problems, and build consensus around potential management strategies. Finally, any new tools for watershed system management need to be flexible and portable, allowing for rapid development and deployment across multiple watershed systems. Building bespoke tools for each individual watershed system is far too costly and time-consuming to serve as a robust and scalable solution for the many watershed systems that need help.

1.5 The Global Water Games Platform

This thesis presents the Global Water Games platform, a general participatory, agent-based framework for building simulation Games for complex socio-ecological watershed systems across the globe. The Global Water Games platform is based on the modeling framework pioneered by the original UVa Bay Game®, but generalized and expanded such that its components can be rapidly reused and redeployed to model a variety of stakeholder objectives in any watershed system worldwide, provided basic input data is available. The watershed system Games built using the Global Water Games platform will be structurally similar to the original UVa Bay Game®, modeling an overall watershed system with a collection of spatially explicit sub-watersheds populated by decision-making agents that represent key stakeholder roles. The Games will be dynamic, modeling a specified time period divided up into a number of discrete time steps. The Global Water Games platform will enable stakeholder participation, both in model creation and during model use, by allowing human participants to control an agent during individual game plays. The watershed simulation Games built using the Global Water Games platform will support effective watershed system management through the dual purposes of policy decision support and facilitating social learning among watershed system stakeholders.

1.5.1 Criteria for Success

There are many requirements for the Global Water Games platform to be successful. The platform must produce watershed simulation Games that are:

- *Spatially explicit,* modeling each watershed system with an appropriate level of spatial granularity to meet stakeholder needs and objectives;
- *Dynamic,* modeling each watershed system with an appropriate level of temporal granularity to meet stakeholder needs and objectives;
- *Agent-based,* representing various types of human stakeholders in each watershed system as decision-making agents that interact with one another and their environment over time;
- *Participatory,* enabling stakeholder participation both during model creation and model use;
- *Validated,* by adequately tracking key metrics observed in real-world data in each watershed system; and

- Supportive the dual purposes of *policy decision support* and *social learning* among stakeholders in each watershed system.

The Global Water Games platform itself must be:

- Sufficiently *flexible* to model a variety of stakeholder needs and objectives in watershed systems around the world;
- *Scalable,* allowing Global Water Games components to be reused and redeployed to support more rapid watershed system model development than building custom models for each one; and
- *Extensible,* to enable new functionality to be incorporated into the platform over time.

1.6 Thesis Outline

The remainder of this thesis is organized as follows. Section 2 reviews the literature on agent-based modeling, participatory modeling, and several previous watershed system modeling efforts. Section 3 lays out the conceptual modeling framework underpinning the Global Water Games platform. Section 4 describes the technical infrastructure currently under development to implement the conceptual framework. Section 5 explores next steps for the Global Water Games platform, and finally Section 6 draws conclusions.

2. Literature Review

2.1 Agent-Based Modeling

Agent-based modeling (ABM) is a relatively new scientific modeling technique that has been enabled by the rise of cheap and abundant computing power. Railsback and Grimm define agent-based models as "models where individuals or agents are described as unique and autonomous entities that usually interact with each other and their environment locally" [24]. ABM eschews traditional reductionist, analytical modeling methods, in which systems are simplified to the greatest degree possible and their elements studied in isolation—an approach that often does not work well for complex systems [3]. Instead, ABM seeks to directly model each element, or "agent," in a system, and then allow the agents to interact with one another in a more "realistic" computer simulation of the complete system. Ottino writes that ABM is "based on the assumption that some phenomena can and should be modeled directly in terms of computer programs (algorithms), rather than in terms of equations" [1].

Agent-based modeling is particularly suited to the challenges commonly encountered when trying to model complex systems, because it sidesteps many of the pitfalls that stymie traditional modeling methods. Railsback and Grimm write that using ABM, "…the limitation of mathematical tractability is removed so we can start addressing problems that require models that are less simplified and include more characteristics of the real problem" [24]. Ottino notes that ABM has, in many cases, begun to "replace equation-based approaches in disciplines such as ecology, traffic optimization, supply networks, and behavior-based economics" [1]. By harnessing the power of computer simulation to capture the interactions between individual entities that constitute a larger system, agent-based modeling provides a method for observing system behavior at various scales—including the micro-level behaviors of individual agents and the *emergence* of macro-level behaviors of the larger system, which are a result of many micro-level interactions between the agents.

Agent-based models are usually validated by comparison with empirical data, but they are often “seeded” with their initial conditions by drawing sample data from a random probability distribution that has no basis in the real world [25]. Hassan, et al, note that the practice of using random initial conditions can have adverse effects on their performance, and propose methods for “injecting” empirical data into agent-based simulations [25]. Matthews, et al, surveyed the practical applications of agent-based techniques in land use modeling, and found ABMs being used for policy analysis and planning, testing potential new social management policies, and participatory modeling, among other applications [26]. With regard to what they describe as “coupled human-environment systems,” the authors observe that there are “many cases where human-environmental interactions are non-linear, with the environment being affected by individual decisions which in turn impact on the environment, potentially leading to complex systems behavior” [26]. The authors note that a major advantage of ABM is “the ability to link social and environmental processes... providing a way of studying human-ecosystem relationships with the ultimate aim of developing principles for managing real coupled human-environment systems” [26].

2.2 Participatory Modeling

Participatory modeling, as applied to natural resource management, is defined as "a diverse range of modelling activities whose common element is that they involve stakeholders at one or more stages of the modelling process," according to Hare [27]. The stakeholder participation can occur at various stages during model creation, during use of a completed model, or both [27, 28]. Hare identifies three purposes for participatory modeling. The first is "direct decision making," or policy decision support. The second is "social learning," in which participating stakeholders from various backgrounds are encouraged to share perspectives with one another and collectively solve problems, potentially leading to new management ideas [27]. The third purpose of participatory modeling is "model improvement"—meaning either the model is more accurate due to leveraging the stakeholders' domain knowledge and expertise, the model is more likely to be accepted and used by stakeholders in practice, the model better integrates diverse perspectives from multiple domains, or some combination of the three [27].

Dreyer and Renn also draw a bright line between policy decision support, which they refer to as "collective decision-making," and social learning as two distinct purposes for participatory modeling [28]. The authors note that involving stakeholders in the model creation phase can help develop an "enhanced understanding of the natural and human systems," at play in a natural resource problem [28]. This enhanced understanding can create "a shared vision of the problem, which may in turn foster mutual understanding between science, management professionals, and stakeholders" [28]. Stakeholder participation in model development and model use can increase transparency in the policy decision-making process, thus building consensus between stakeholders, enhancing the credibility and legitimacy of resulting policy decisions, and improving ultimate policy compliance [28]. The authors warn, however, that if a participatory modeling exercise is too complicated and it can still be incomprehensible and opaque to stakeholders and decision makers, despite their involvement [28]. They also caution that effectively achieving both policy decision support and social learning within the same modeling framework can be a considerable challenge [28].

Matthews, et al, agrees that the strength of the participatory modeling approach—whether it involves stakeholders in model creation or simply model use—is that stakeholders become exposed to viewpoints different than their own about the same natural resource problem, enabling them to explore options they may not have considered before [26]. The authors also observe that real decision makers and stakeholders actually use surprisingly few policy decision support systems in the field, even when such systems are specifically tailored for their use. They attribute this to model builders' poor understanding of the stakeholders' true needs and real decision-making process, a problem that could potentially be alleviated by stakeholder input during model creation [26]. The authors note that stakeholder participation in model development has downsides—namely, the time and cost of involving stakeholders, and the possible loss of academic credibility for the resulting model—but argue that the extra "buy-in" and trust from stakeholders is worth the cost [26].

Various flavors of participatory modeling exercises have been used frequently for management of water resources, such as in the "Floodplain Management Game" in Stefanska, et al [29], and in the Baixo Guadiana River Basin in Portugal in Videira, Antunes, and Santos [30].

2.3 Agent-Based Participatory Simulation

Agent-based modeling and participatory modeling can be merged into a single new approach known as *agent-based participatory simulation* [31]. Agent-based participatory simulations feature stakeholder participation in model use by allowing human participants to control an agent in the simulation via a computer interface [31]. By controlling one of the agents, human participants act “exactly as if they were part of an agent-based simulation” [31]. Guyot and Honiden note that since all participants are using individual computers, and interactions take place through the computer interface, all actions can easily be recorded and processed on the fly—a significant advantage over previous participatory modeling approaches [31]. Briot, Guyot, and Irving identify several further benefits to the agent-based participatory simulation approach. First, agent-based participatory simulation enables the participation of stakeholders who are geographically distant [32]. Second, in the event that not enough human participants are available to take part in the simulation, some participants to be replaced by artificial agents [32]. Briot, et al, uses the approach to implement “SimParc,” an agent-based participatory simulation framework designed to explore participatory management of protected areas, such as national parks [32, 33]. According to Briot, Guyot, and Irving, agent-based participatory simulations allow stakeholders to “use the simulation to let them define and introduce participatory management practices” [32].

2.4 Review of Selected Previous Watershed System Modeling Efforts

There have been numerous previous efforts to model watershed systems for various management-related purposes. I review three of them here—the World Resources Institute's Aqueduct Water Risk Framework, the Stockholm Environment Institute's Water Evaluation and Planning (WEAP) System, and DANUBIA, an integrated simulation model of the Upper Danube watershed system in Europe.

2.4.1 Aqueduct Water Risk Framework

The Aqueduct Water Risk Framework is a methodology for measuring water risks associated with specific geographic areas worldwide [34]. It is intended primarily to help private companies and investors better judge the risks water-related issues pose for business. It is based on twelve basic water risk indicators for which data is available globally, such as seasonal variability in water supply, the percent of the local population with access to safe and reliable drinking water, and so on [34]. The Framework groups these twelve indicators into three water risk categories: quantity risk, quality risk, and regulatory/reputational risk (which is defined as the potential for conflict with the public that could damage a business's reputation or legal standing) [34]. The Framework uses this input data to calculate overall, aggregated scores for water risk for most geographic locations worldwide [34]. For a given area, the aggregated water risk score is a weighted average of the original twelve water risk indicators [34]. Users can also break out scores for any of the three risk categories or the original twelve indicators themselves. The Framework gives users a degree of flexibility by allowing them to select the weights for each of the indicators to reflect their own objectives and values, or users can choose one of twelve "weighting profiles" preset for specific industry sectors [34]. The resulting aggregate water risk scores can be visualized and displayed on maps for easy interpretation, and to easily compare the water risk scores between different locations. These maps can be accessed online through a web-based interface.

The Aqueduct Water Risk Framework is useful to get a static snapshot of the degree of water risks in a given watershed system, or of locations within watershed systems. It is also helpful to quickly compare the relative water risks between different geographic areas or watershed systems. Though the Aqueduct Water Risk Framework is designed first and foremost for business use, the water risk scores it produces could be of interest to a wide variety of governments, non-government organizations, and private individuals.

2.4.2 Water Evaluation and Planning (WEAP) System

The Stockholm Environment Institute's Water Evaluation and Planning (WEAP) System aims to be a policy-oriented tool for simulating water systems for water resources planning [35]. The intended user is a skilled water planner for policy analysis purposes [35]. WEAP can be used to simulate municipal or agricultural water systems, individual sub basins, or larger river systems [35].

WEAP provides users with an integrated software interface with which to build water system simulations. WEAP's modeling methodology incorporates both water demand and water supply in water systems, as well as basic ecosystem requirements. It represents water systems or parts of water systems in terms of discrete supply sources, withdrawal points, storage reservoirs, transmission and wastewater facilities, pollution generation points, etc., and the flow relationships between them [35]. To model a given water system, the user sets up these discrete modeling elements, specifies their properties and “Current Accounts,” or current state, and links them together with the appropriate relationships [35]. The WEAP software then allows the user to simulate water demand, supply, flows, and storage, for future states of the system in a deterministic manner [35].

WEAP is particularly helpful to allow skilled water planners to address “what if” questions in basic water systems. For example, say a planner wanted to explore the effect of population increases on water resources in a city. WEAP would allow the planner to build a basic simulation model of the water sources and facilities that make up the municipal water system, and then run the simulation in which the “population” parameter deterministically increases by 10%. The simulation model would help the planner identify any changes in the balance between water demand and available water supplies over time.

2.4.3 DANUBIA

DANUBIA is an integrative simulation model and decision support system designed for the Upper Danube watershed in Central Europe [36]. It was created by GLOWA-Danube, a program focused on a holistic analysis of the future of water resources in the Upper Danube Basin [36]. It links or “couples” numerous dynamic simulation models focused on single natural science or socioeconomic domains, such as hydrology, plant ecology, meteorology, farming, tourism, etc., into a unified “integrated” simulation model applied to the Danube watershed system [36]. The simulation models focused on socioeconomic domains are agent-based. All of the component simulation models are connected to a single central database that stores all GIS data and statistics, ensuring all of the coupled models are working off of the same input data. The unified simulation model is computationally intensive, and runs on a distributed server cluster [36].

DANUBIA's objectives are threefold. First, it aims to demonstrate the viability of the integrative simulation approach. Second, it attempts to identify dependencies and feedbacks between processes in the different individual domain models. Finally, it seeks to support decision-makers in crafting policy through comprehensive analysis of the water resources available in the Upper Danube Basin over time [36].

2.4.4 Evaluation of Previous Watershed System Modeling Efforts

Each of the three previous watershed system modeling methodologies reviewed here—the Aqueduct Water Risk Framework, the WEAP system, and DANUBIA—are useful for their specific applications. However, when judged against the benchmark of the requirements set out for Global Water Games, namely that the watershed system models they produce are *spatially explicit, dynamic, agent-based, participatory,* and serve the dual purposes of *policy support* and *social learning*, none of these previous efforts would fit the bill. Each of the methodologies would meet certain requirements—for example, all three are spatially explicit. But they all fall short in specific key areas. The Aqueduct Water Risk Framework provides a static snapshot of a watershed system, not a dynamic model. Both Aqueduct and WEAP lack any agent-based modeling component, leaving them with no way to represent the complex impact human decision-making has on the outcomes of watershed systems over time. Critically, all three lack a mechanism to enable robust stakeholder involvement in model creation and model use, which can reduce the degree to which stakeholders understand, trust, and comply with the policy recommendations generated through the model, and calls into question their ability to foster meaningful social learning among system stakeholders [26, 27, 28]. Figure 3 presents a visual review of the various watershed system modeling approaches versus a selection of the Global Water Games platform's criteria for success presented in Section 1.5.1.

	Spatially Explicit	Dynamic	Agent-Based	Participatory	Flexible
Aqueduct	x				x
WEAP	x	x			x
DANUBIA	x	x	x		
UVA Bay Game	x	x	x	x	
Global Water Games	x	x	x	x	x

Figure 3. A comparison of the Aqueduct, WEAP, DANUBIA, UVa Bay Game®, and Global Water Games approaches to watershed system modeling versus a selection of the criteria for success outlined in Section 1.5.1.

3. Conceptual Framework

3.1 Overview of the Conceptual Framework

At the highest level, the Global Water Games platform seeks to describe both the ecological and human elements of a watershed system, and how the interactions between the two produce system-level outcomes, both social and ecological, that are critical to local stakeholders. It seeks to be dynamic, modeling how these interactions and the system-level outcomes they produce evolve over time. The framework is also designed to be as general as possible. Within a single modeling architecture, many different watershed systems around the world can be simulated, while preserving maximal flexibility for modelers and local stakeholders to customize a given watershed model to their own particular social and ecological concerns.

The Global Water Games platform achieves these aims by creating a spatially explicit geographical representation of the watershed and overlaying it with a set of "stakeholder-agents" that represent the human actors in the watershed system. The methodology breaks down the geographic area of a watershed system into mutually exclusive and collectively exhaustive sub-watersheds—known as hydrologic units (HUs)—at multiple scales. These hydrologic units serve as the basic spatial modeling units of the framework. The hydrologic units are populated with a set of "stakeholder-agents" (or simply "agents") that represent various types of human entities that reside throughout the watershed system. These agents can represent individuals, businesses, organizations, or government entities that rely on the watershed for critical services and whose actions can have a material impact on its outcomes. The methodology uses a discrete model for time, with each unit of time represented by a discrete "step"—such as one month or one year. At each time step, each stakeholder-agent makes a series of economically and ecologically relevant decisions according to the role that agent plays in the watershed system. Each agent's decisions are influenced by both information about the social and ecological state of the watershed system and the state of the agent's own characteristics (such as financial position) at the current time step. At the end of each time step, the model aggregates the effects of all agents' decisions, and combines them with natural forces, historical trends, and any exogenous factors, to update the state of the watershed system and calculate the system-level outcomes of interest. By applying this process iteratively through a set number of time steps, the model can track all actions and outcomes at multiple geographic scales throughout the time period under consideration.

The framework uses three main conceptual modules components to model the physical and human elements of the watershed system and their interactions through time:

- The *Spatial Module* contains the set of hydrologic units (HUs) that make up the watershed system, and is responsible for representing the spatially distributed social and ecological characteristics of the watershed system.
- The *Stakeholder Module* contains all of the stakeholder-agents in the model and their relevant individual characteristics, including stakeholder role.
- The *Model Update Logic* contains the instructions that update the state of the watershed system and its system-level outcomes from one time step to the next, based on the aggregate effects of the agents' decisions, natural forces, historical trends, and any exogenous factors.

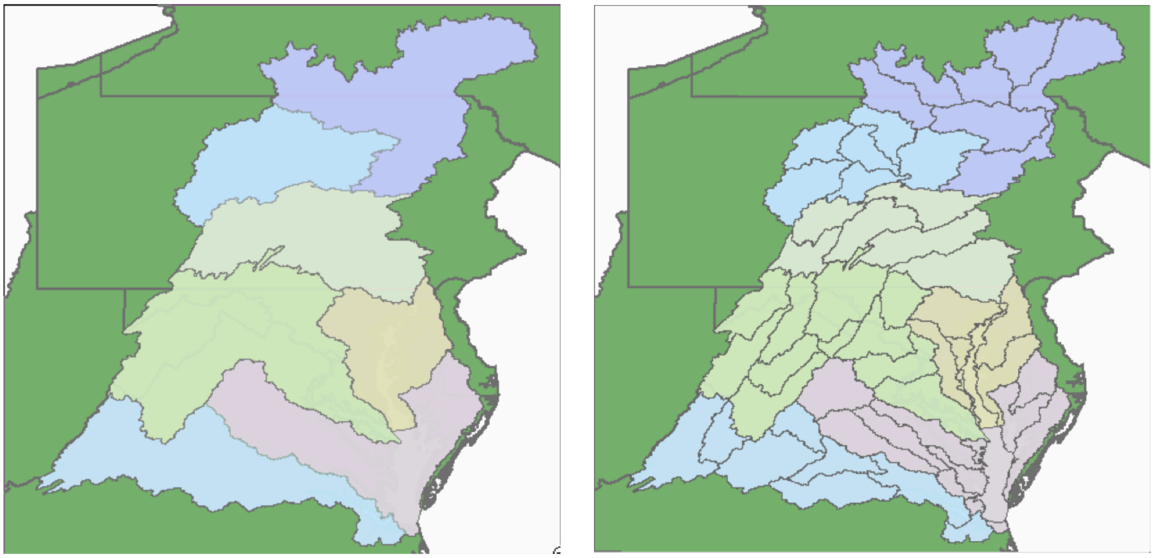
I examine each module in the conceptual framework in detail below.

3.2 The Spatial Module

The Spatial Module is composed of the set of sub-watersheds, or hydrologic units (HUs), that together constitute the larger overall watershed system. Thanks to the branching tree structure typical of river systems, any larger watershed can be broken down into a number of sub-watersheds at multiple scales. In the complete watershed of a principal river, the first "level" of sub-watersheds would be the watersheds of its primary tributaries. Taken together, the watersheds of all the principal river's primary tributaries are mutually exclusive in area between one another, and collectively exhaustive of the area of the principal river's complete watershed. The second "level" of sub-watersheds would be the watersheds of the tributaries of the first-level tributaries. Again, taken together, the watersheds of the second-level tributaries, while smaller and more numerous, are mutually exclusive between each other and collectively exhaustive of both the primary tributaries' watersheds and the overall principal river's watershed. By continuing this process up the chain of tributaries, it is possible to completely subdivide any larger watershed into a set of smaller, hydrologically coherent geographical units at multiple scales.

For watersheds in the United States, the USGS has published a standardized database of hydrologic units covering the entire geographical area of the country [37]. The USGS has identified hydrologic units at six different scales ranging from the highest level, covering entire regions of the country, down to the lowest level, covering the catchment areas of local streams. Typically, each hydrologic unit represents one drainage basin with a single outlet, which can represent either the terminus of the river system (e.g., an ocean) or the beginning of the next hydrologic unit further downstream [38].

There are occasional exceptions, such as along some coastlines where individual drainage streams are too small to receive their own hydrologic unit, and the USGS has combined several into a single unit [37]. Each hydrologic unit is assigned a unique numeric identifier code, with a number of digits corresponding to the unit's level in the hierarchy. The different levels are denoted as Hydrologic Unit Code 2, 4, 6, 8, 10, and 12 (also written HUC-2, HUC-4, and so on). The highest-level HUC-2 units will have a unique two-digit identifier, such as the unit HUC-02, which covers the Mid-Atlantic Region on the US East Coast. Each HUC-2 unit is made up of a number of HUC-4 units, which themselves are made up of a number of HUC-6 units, and so on. The first two digits of any HUC identifier code will correspond to the HUC-2 unit of which it is a part; the first four digits will indicate its HUC-4 unit (if applicable), and so on. For example, the Mid-Atlantic Region is HUC-02, which encompasses all or part of the states from Virginia to New York. The Lower Chesapeake is an HUC-4 unit covering much of Virginia and parts of West Virginia; it's contained within the Mid-Atlantic Region (HUC-02) and has the identifier HUC-0208. The James River watershed is defined as an HUC-6 unit that is within both the Mid-Atlantic Region (HUC-02) and the Lower Chesapeake (HUC-0208), so its identifier is HUC-020802. The Rivanna, the main river that flows through Charlottesville, Virginia, and a tributary of the James, anchors an HUC-8 unit in Central Virginia, contained within the James' larger HUC-6. The USGS defines an additional two levels of more detailed hydrologic units beyond that, the HUC-10 and HUC-12 levels [38]. Figure 4 shows a map of hydrologic units in the Chesapeake Bay watershed at both the HUC-6 and HUC-8 level.



HUC-6 **HUC-8**

Figure 4. The Chesapeake Bay watershed, divided into hydrologic units at multiple scales. Hydrologic units are shown at the HUC-6 level, at left, and at the HUC-8 level, at right. Each HUC-6 unit is made up of a set of the smaller HUC-8 units. Colors in the HUC-8 figure on the right show the boundaries of the larger HUC-6 units and are included for reference; they do not indicate any necessary or required grouping of HUC-8 units. Data sourced from the Watershed Boundary Dataset [39].

Outside of the United States, there may be government agencies analogous to the USGS that produce and publish similar maps of hydrologic units for their geographies. If no such maps of hydrologic units are publically available for a given geographic region, the modelers can create them using a Digital Elevation Model (See Appendix A for more information). Thanks to NASA's Shuttle Radar Topography Mission, reliable Digital Elevation Models can be found on a near-global scale [40].

Early in each model creation process, the modelers and local stakeholders work together to determine the smallest level of hydrologic units to use in a given model, depending on the level of geographic granularity required to achieve the model's objectives. These hydrologic units (HUs) provide a particularly useful basic spatial unit for modeling watershed systems. Since most HUs represent a single drainage basin, all hydrologically relevant activity, both human and ecological, that occurs within the geographic footprint of a HU is related, since all water runoff within the unit will eventually flow together to the single outlet. Given that the HUs are delineated according to the characteristic branching tree structure of the river system under consideration, it is simple to link them together in a network model, or "hydrologic link network," that specifies the upstream/downstream relationships between them. This provides a convenient way to trace the effects that actions in upstream areas have on HUs further downstream in the river system. Figure 5 shows an example hydrologic link model for the James River watershed using HUs at the HUC-8 level. Due to the inherent hierarchical, multi-scale nature of HUs, it is simple to aggregate or "roll up" data from the smallest basic units to the larger HUs of which they are a part, at multiple scales, all the way up to the full watershed system. Finally, the set of hydrologic units published by the U.S. Geological Survey serve as an extremely useful starting point for building a set of HUs to use for a Global Water Game, but the modelers are not bound to use them exclusively. The modelers may use the HUs published by the U.S. Geological Survey at a particular HUC level as-is, or they may combine or aggregate different units or sub-watershed areas as desired to create a set of hydrologic units that best serve the stakeholders' needs and objectives for their Global Water Game.

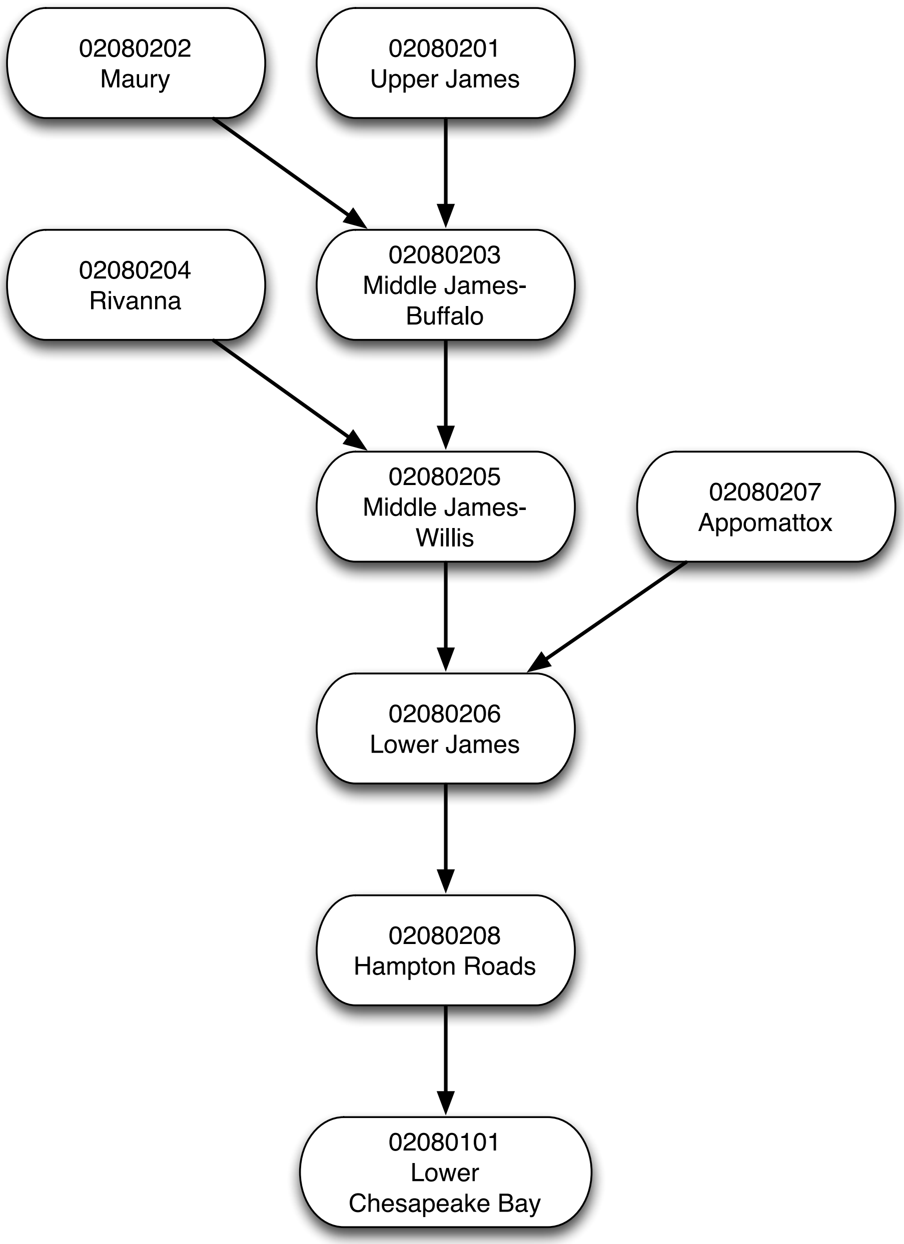


Figure 5. A visual representation of the hydrologic unit link network at the HUC-8 level for the James River watershed. The ovals represent HUC-8 hydrologic units, labeled by their Hydrologic Unit Code and name, while the arrows represent the upstream/downstream (direction of water flow) relationships between the HUs. Data sourced from the Watershed Boundary Dataset [39].

As the basic spatial unit of the modeling framework, each HU in the Spatial Module contains a set of geographically distributed ecological and social variables that affect the system-level outcomes of interest. For each HU, these variables represent the value of the characteristic in question corresponding to the geographic extent of the HU—for example, the total flow rate coming from the HU, or the total population living within the HU's area. These variables associated with the individual HUs are referred to as "spatial state variables" or simply *spatial variables*. These variables are usually dynamic and change from one time step to the next. Taken together, they represent the state of the watershed system for all spatially distributed features at a given time step.

The particular spatial variables used in an individual Global Water Games model will vary depending on local stakeholders' needs and objectives, the system-level outcomes of interest, and any unique characteristics of the watershed system under consideration. However, certain types of spatial variables are likely to be useful for many of Global Water Games models. These general categories of spatial variables include:

- **Area** — The total land area of the HU.
- **Flow Rate** — The total volume of water runoff from the HU in the current time step.
- **Water Quality Variables** — One or more variables measuring certain aspects of water quality, including salinity, sediment load, nitrogen load, phosphorus load, etc.

- **Precipitation/Climate** — The total volume of precipitation within the HU in the current time step. Depending on the individual model, additional climate variables, such as temperature, may be relevant.
- **Population** — The total number of people living within the HU in the current time step.
- **Land Use** — The proportion of the HU's total area that is devoted to agriculture, urban development, natural vegetation, barren land, etc.
- **Economic Data** — Depending on the individual model, a number of economic variables may be required, such as jobs/unemployment, GDP, industrial output, land value, etc.
- **Agriculture/Aquaculture Data** — Depending on the individual model, a number of agriculture or aquaculture variables may be required, such as acreage under cultivation for certain crops, populations of livestock, populations of fish or other aquatic fauna, etc.
- **Land Use and Water Use Policies** — Land Use and Water Use policies are special types of spatial variable in the model. They reflect societal regulations that potentially incentivize or constrain stakeholders' use of certain resources or management practices in the HU.

In order to forecast or project the values of all spatial variables from one time step to the next, each HU in the Spatial Module also has an associated mathematical "trend function" for each of its spatial variables that models any exogenous, observed historical trends in its value. For example, for the population variable, a given HU may have experienced a certain annual percentage increase in its population, based on historical data. In the model creation phase, this trend in the HU's population variable would be captured and stored as a mathematical function. Different types of spatial variables are likely to require different types of trend functions to accurately model systematic changes in their historical values over time. The modelers could plausibly use many types of mathematical functions, from very simple to as complicated as required, to represent historical trends in spatial variables for each HU. Several types of trend functions that are likely to appear in most watershed models include:

- **Constant Value (No Trend)** — The value of the variable is found to not change over time in the historical data (possibly with only minor variation). In this case, there would be no trend or seasonality in the variable and the "best" forecast of a future period is the current value. Certain variables, such as the land area of HUs, would not be expected to change over time. Alternatively, when there is insufficient historical data to establish a reliable trend for a particular spatial variable, it may be prudent to use the current time step's value as the best base estimate for the next step's.
- **Linear Change** —The value of the variable changes by a fixed quantity from one time step to the next. This sort of model would be appropriate for a historical dataset where there is a monotonic trend either increasing or decreasing by a constant value.
- **Percent Change (Exponential Growth/Decay)** — The value of the variable changes by fixed percentage relative to its current value from one time step to the next. For example, if the historical data shows annual population growth of a

roughly constant percentage within a given HU, an exponential growth trend function may be called for.

- **ARMA/ARIMA Model** — For variables with a more complicated historical record, ARMA or ARIMA (Autoregressive [Integrated] Moving Average) time series models could be developed where a combination of autoregressive and/or moving average terms is estimated after possible differencing. Typically, such models have only a few parameters to estimate. ARMA or ARIMA models may be appropriate for flow rate, climate, economic, or any other types of variables expected to follow characteristic seasonal or cyclical patterns.
- **Stochastic Variation** — Certain variables may generally follow one of the other types of trend functions (including constant value—no trend), but modified by an element of stochastic variation each time period. For example, the amount of precipitation within a given HU might generally conform to an ARMA model, but with random fluctuations within each time period to account for unusually wet or dry periods. Including an appropriate stochastic random variable in its trend function could simulate this additional variability.

When selecting trend functions for the spatial variables for each HU, the modelers must take care only to include the effects historical trends caused by natural or otherwise exogenous forces, such as climate or overall economic conditions, and exclude trends primarily caused by the activities of human stakeholders represented by agents in the model. For example, the historical record for Land Use variables for many HUs that contain urban or suburban areas may show a decline over time in the total area of land used for natural vegetation, and a corresponding increase in the total area of land used for urban development. This trend is likely strongly linked to the activities of land developer stakeholders in the region. If the Global Water Games model under development includes Land Developer as one of the roles agents can take on, the model will account for these land use changes explicitly through the decisions of agents in the Land Developer role. If the modelers also include a positive or negative trend function for these land use variables based on historical data of land development activity, it could introduce double-counting of the effects of land developer stakeholders in the watershed system. For more information about how to build the set of HUs, set the initial values for the spatial variables for each HU, and prepare historical data to determine trend functions for a given watershed system, please see Appendix A.

The set of HUs and their associated spatial variables that constitute the Spatial Module are sufficient to completely specify the ecological and societal state of a given watershed system model at a particular time step. The Spatial Module alone, however, is not sufficient to represent individual human actors in the watershed system, and capture the effect of their individual and collective decision-making on system-level outcomes over time. Nor does it alone enable stakeholder participation in model use. To provide these capabilities, we need the next module.

3.3 The Stakeholder Module

The second main conceptual module, the Stakeholder Module, is responsible for representing the effects of human entities within the watershed system, and for providing the model's agent-based and participatory simulation functionality. It consists of the set of all stakeholder-agents in the watershed system model, and their associated individual characteristics. These stakeholder-agents represent the different kinds of human-controlled stakeholders—individuals, businesses, organizations, or government agencies—active within the watershed system who rely on it for critical services, and whose individual decisions and actions can have a meaningful impact its on the system-level outcomes. Each stakeholder-agent is assigned to one of a predefined set of *stakeholder roles* (or simply “roles”), each of which represents a general category of human-controlled stakeholder operating in the watershed system. During the model creation process, the modelers and local stakeholders work together to determine the set of stakeholder roles required for a given Global Water Games model, based on the local stakeholders’ needs and objectives and the characteristics of the particular watershed system being simulated. Not every Global Water Games model will require the same set of stakeholder roles; however, many will likely require certain general types, including:

- **Citizen** — General residents of the watershed system who are concerned about water use in their daily lives.
- **Crop Farmer** — Farmers who grow crops and are concerned about which crops to grow, how many acres to plant, different agricultural management practices, etc.
- **Animal Farmer/Rancher** — Farmers who raise livestock and/or poultry and are concerned about herd or flock size and between different management practices.
- **Land Developer** — Economic actors who are concerned about purchasing, developing, and reselling land, and associated business practices.

- **Industrial Actor** — Businesses that are concerned about industrial water use and management practices.
- **Land Regulator** — Government representatives who regulate (i.e., incentivize, discourage, or constrain) the activities of other agents involving land use, such as land management practices for agriculture or land development.
- **Water Regulator** — Government representatives who regulate the activities of other agents involving water use, such as direct water consumption, contamination, and use of other water-based resources (e.g., populations of fish or other aquatic fauna).
- **Government Non-regulator** — Non-regulatory government actors, for example military bases, that are concerned about their water use practices.
- **Custom** — Many Global Water Games models will require custom stakeholder roles, based on the unique characteristics of the watershed system being modeled. The "waterman" (crab fisherman) role in the UVA Bay Game® would be an example of a custom stakeholder role.

Each agent contains a set of individual characteristics, or *agent variables*. Most agents will have variables that represent their financial position; beyond that, the specific agent variables associated with each agent will depend on the agent's stakeholder role. For example, the agent variables for an agent in the Animal Farmer role would include the number and type of animals owned, while an Industrial Actor agent would have an agent variable for the number of industrial facilities in operation. These agent variables are dynamic and may change from one time step to the next based on the agent's decisions and the prevailing system-level conditions. Similar to the spatial variables for HUs, taken together, the agent variables specify the "state of the system" for each agent. The modelers and the local stakeholders define the particular list of agent variables used for each stakeholder role during the model creation process.

During each time step in a model run, each agent makes a series of economically and ecologically relevant decisions corresponding to the agent's role. These decisions will determine the agent's individual impact on the outcomes of the watershed system. For example, at each time step, an agent in the Crop Farmer role may need to decide which crops to plant, how many acres of each, and what kind of agricultural management practices to use, while an agent in the Land Developer role may need to decide how much land to buy or sell, what kind of improvements to make, and what kind of construction land management practices to use. An agent in a Land Regulator role may make decisions (i.e., set government policies) designed to influence the decisions made by Crop Farmer, Land Developer, and other land-intensive agents. Each decision an agent makes falls into one or more general categories, based on its effects:

- **Type 1** — Directly affects one or more spatial variables. For example, an Industrial Actor agent may decide to increase manufacturing activity, which would consume more water. This decision would directly reduce the local flow rate, a spatial variable.
- **Type 2** — Directly affects one or more agent variables. For example, a Land Developer agent may decide to sell land. This decision would directly increase the agent's own financial position, but decrease the number of acres owned, both agent variables.

- **Type 3** — Decisions that affect the Land Use Policy or Water Use Policy variables for an HU. These decisions are made by regulator agents and influence or constrain the decision space of other stakeholder roles. For example, a Land Regulator agent may ban certain undesirable agricultural land management practices. This decision doesn't have a direct impact on any spatial or agent variables itself, but it alters the decision space for Crop Farmers, whose decisions do have a direct effect.

The modelers consult with stakeholders during model creation to determine the set of decisions agents in each stakeholder role will make. They can use Type 1, Type 2, and Type 3 effects as a guide to determining which decisions are relevant to include in the model. If a given type of real-world stakeholder makes a certain type of decision on a recurring basis and it has significant Type 1, Type 2, or Type 3 effects, the decision likely belongs in the watershed model.

In addition to a stakeholder role, each agent is assigned to an individual "home" HU in the Spatial Module, which represents where the agent "lives" in the watershed system. This local HU serves as the "functional space" for the agent's decisions in the simulation model. The impact of any and all Type 1 decisions that each agent makes in a given time period have an impact on the spatial variables of the agent's local HU for the following time period. This allows modelers to distribute the agents geographically throughout the watershed model in a way that roughly reflects the relative distribution of stakeholders in the real-world watershed system. It also allows the spatial effects of the agents' decisions to be captured locally, through the agent's home HU, and globally, by "rolling up" the spatial variables of multiple HUs into larger regions.

Taken together, the Spatial Module and Stakeholder Module completely specify the ecological and social state of the watershed system, at multiple scales, at a given point in time. To make the model dynamic, though, we need a third module—logic that is capable of integrating information about natural forces and agent decisions to update the state of the watershed system over time.

3.4 Model Update Logic

The final module in the conceptual framework is the Model Update Logic. It allows the watershed system model to be dynamic and move forward through time. The Model Update Logic contains instructions about how to integrate information about natural forces and agent decisions at a given time step, and use that information to calculate the value of each state variable for the next time step. It updates all spatial variables for all HUs and agent variables for all stakeholder-agents from one time step to the next, thus updating the complete state of the system in the watershed model.

The Model Update Logic contains a general mathematical "update function" for each type of spatial variable. These update functions accept a number of relevant inputs that represent factors that have a meaningful impact on the type of spatial variable in question. At the end of each time step, the Model Update Logic applies the appropriate update function to each spatial variable in each HU in the Spatial Module to update their values for the next time step. The general spatial variable update function accepts six types of inputs:

- **Current State** — For many spatial variables, such as population, land use, economic data, etc., the variable's current value is the starting point for the value of the variable at the next time step, modified by the effects of the other inputs.
- **Agent Decisions** — Many agent decisions have Type 1 effects—a direct impact on one or more spatial variables in their local HU. Each spatial variable update function contains logic mapping how of each type of agent decision from agents within the local HU affects the value of the relevant spatial variable at the next time step.
- **Local Natural Forces** — Natural forces present in the local HU will affect the updated values of some spatial variables. For example, a Sediment Load spatial variable for a given HU might increase or decrease from one time step to the next due to natural forces present in the HU.
- **Upstream Effects** — For certain types of spatial variables, particularly water quality variables, the value of the variable in upstream HUs may have a relevant impact on the value of the variable in HUs further downstream. Due to the single-outlet nature of most HUs, all runoff from an upstream HU will ultimately flow through any downstream HUs. For example, say we are considering a downstream HU that has one additional HU further upstream in the hydrologic link model of a particular watershed. If agent decisions in the upstream HU cause it to have a substantial increase in its nitrogen load variable at the next time step, that increase may influence the nitrogen load variable at the next time step in the downstream HU as well.

- **Historical Trends** — As noted in the *Spatial Component* section, each HU has an associated historical trend function for each of its spatial variables that reflects any exogenous, observed historical trends in the variable's value in the HU over time. The spatial variable update functions accept these trend functions as inputs in their wider calculations.
- **Exogenous Factors** — The update functions can take additional exogenous factors into account. For example, the modelers may wish to explore the effects of natural disasters, or other extreme events, that would have a meaningful impact on one or more spatial variables. These extreme events are not represented within the normal modeling framework, but can be captured via an additional input to the spatial variable update functions.

The general form of the spatial variable update function can be seen in Figure 6.

$$SV_{t+1} = SV_t + AD_t + NF_t + UE_t + HT_t + EX_t$$

Figure 6. The general form of the spatial variable update function. *SV*(t+1) represents the value of the spatial variable at the next time step; *SV*(t) represents the value of the variable at the current time step. *AD*, *NF*, *UE*, *HT*, and *EX* represent the effects of agent decisions, natural forces, upstream effects, the historical trend, and exogenous factors, respectively, at the current time step.

Similarly to the general spatial variable update functions, the Model Update Logic contains a general update function for each type of agent variable for each stakeholder role. These agent variable update functions also accept several types of inputs:

- **Current State** — For many agent variables for various stakeholder roles, such as financial position, number of livestock owned, number of acres owned, etc., the current value will serve as the starting point for the next time step's value, modified by the effects of the other inputs.
- **Agent Decisions** — Most decisions that an agent makes at a given time step will directly affect the value of one or more of that agent's variables at the next time step. If a Land Developer agent decides to purchase land, that decision will have a direct impact on two of that agent's own variables—positive for number of acres owned, and negative for financial position.
- **Spatial Variables** — The updated value of some agent variables may depend on the value of related spatial variables in the local HU at the current time step. For example, if a Crop Farmer agent has a number of acres of a climate-sensitive crop under cultivation, an agent variable, the precipitation or temperature variables of the local HU, themselves spatial variables, could potentially reduce the number of acres under cultivation at the next time step.
- **Exogenous Factors** — Similarly to the spatial variable update function, the modelers may want to take exogenous extreme events that would affect agent variables into account. These events are not represented within the normal modeling framework, but their effects could be captured with an exogenous factors input in agent variable update functions.

The general form of the agent variable update function can be seen in Figure 7.

$$AV_{t+1} = AV_t + AD_t + SV_t + EX_t$$

Figure 7. The general form of the agent variable update function. *AV*(t+1) represents the value of the agent variable at the next time step; *AV*(t) represents the value of the variable at the current time step. *AD*, *SV*, and *EX* represent the effects of the agent's own decisions, the values of any relevant spatial variables in the local HU, and exogenous factors, respectively, at the current time step.

The inputs to the general update functions for both spatial variables and agent variables will often themselves be smaller functions. The Agent Decisions, Local Natural Forces, Upstream Effects, and Historical Trends inputs for the general spatial variable update functions will all likely be functions, as well as Agent Decisions and Spatial Variables inputs for the agent variable update functions. During the model creation phase, the modelers will define these intermediate input functions that map the effects of the various input factors to outcomes for each spatial variable and each agent variable for all stakeholder roles. These input functions can range from very simple to as complicated as required. Depending on the variables involved, the objectives of the local stakeholders, and the unique characteristics of the watershed system under consideration, the modelers may create or generate these intermediate mapping functions themselves, or they may draw from existing scientifically accepted models. An Industrial Actor's decision to consume more or less water for industrial activity will likely have a simple, one-to-one linear relationship with the flow rate spatial variable in the local HU. This relationship would be captured by a linear function in the Agent Decision input function within the general spatial variable update function for the flow rate variable, which the modelers could easily define. On the other hand, some input factors may have more complicated relationships with their target spatial or agent variables. For example, decisions by Crop Farmer agents to use various types of agricultural land management practices may have a more complicated relationship with certain water quality variables, such as the nitrogen load, in both the local HU and any HUs further downstream. In these more complicated scenarios, like mapping the effects of upstream nitrogen sources to the nitrogen loads in downstream HUs, the modelers may choose to incorporate existing scientific models, such at the USGS's SPARROW model for nutrient loading, as intermediate input functions [41].

A diagram of the overall structure of the Conceptual Framework, its three constituent Modules, and the relationships between them can be seen in Figure 8.

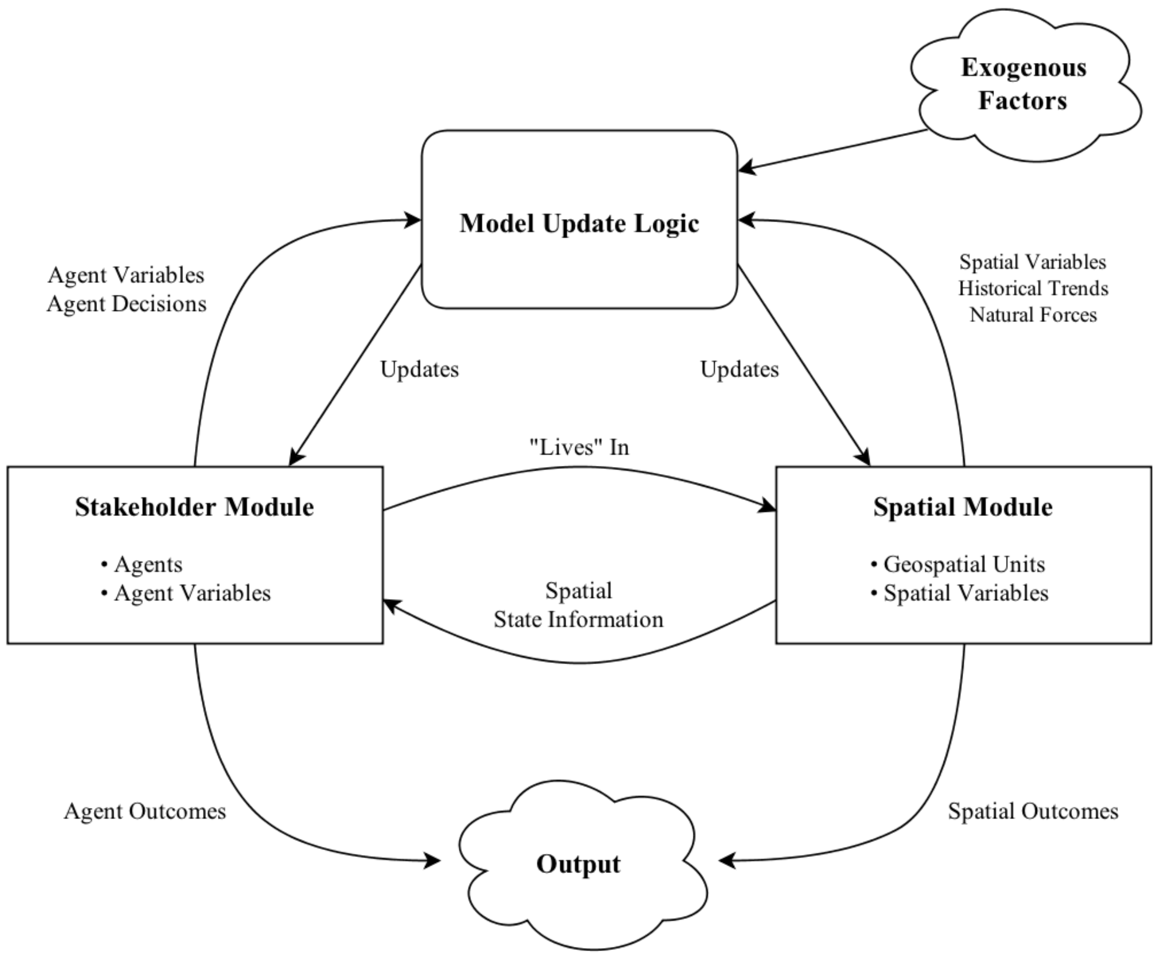


Figure 8. The overall structure of the Conceptual Framework, its three constituent Modules (the Spatial Module, the Stakeholder Module, and the Model Update Logic), and the relationships between them.

3.5 Model Use: Game Plays

The operational use of a completed Global Water Games model is centered on numerous discrete "game plays" of the model. Each individual game play of a given Global Water Game is one complete run of the simulation model through all time steps in the time period under consideration, from start to finish. Game plays involve active human interaction from two groups: the game facilitators and game participants. The game facilitators are typically, but not necessarily, the same modelers who originally created the Global Water Games simulation. A different group of participants, both in who the participants are and often their total number, take part in each game play. Each game play occurs at a specific, pre-arranged time, during which all participants will interact with the game simultaneously.

Prior to starting a game play, the facilitators hold an orientation with the participants to discuss the watershed system model, its objectives, and the significance of the macro-scale challenges facing the watershed system. They also instruct the participants about how to interact with the model's user interface. The facilitators initialize the model by resetting all of the state variables, spatial and agent, to their initial values for the first time step. During model initialization, each human participant is assigned to a particular agent in the model. The participant assumes the "identity" of the agent to which they're assigned in the game, taking on its stakeholder role, location (i.e. home HU), and agent variables. The participants will "play" the game by controlling the decisions that their agent makes in the model, and thus its individual contribution the larger, system-level outcomes of the watershed simulation model. Allowing humans to play a Global Water Game in this manner—by putting themselves in the "shoes" of a single agent acting in a particular stakeholder role—enables direct stakeholder participation in the use of the simulation models.

At each time step during game play, all human participants make the decisions for their assigned agents concurrently. The Game's user interface presents each participant with customized information based on the participant's stakeholder role and location (i.e., HU). The data presented to each participant include the current values for a relevant combination of spatial and agent variables, including their agent's own variables (such as financial position or number of acres owned), current spatial variables in the local HU (such as local flow rate or local unemployment), and certain system-level variables (such as an overall watershed system flow rate). Each participant uses this customized information to make a set of decisions based on their stakeholder role, and input their decisions back into the user interface.

As the participants make their decisions, they are free and encouraged to communicate with one another. Participants may choose to communicate to try to further their agent's interests in the simulation model. For example, several participants in the same stakeholder role that relies on a scarce natural resource may choose to negotiate and coordinate their decision-making around the resource. In another example, participants in certain stakeholder roles, such as crop farmers—whose decisions are regulated or incentivized by policies set by participants who control agents in relevant regulatory roles—may choose to apply social pressure on regulator participants to try to influence them to set more advantageous regulatory policies. There are a wide variety of scenarios in which communication, negotiation, and coordination between participants, or a lack thereof, could affect the system-level behaviors of the simulation model.

The game facilitators control the "flow" of the game play. Once all of the participants have completed their decisions for a given time step, the facilitators use a specialized interface to advance the game play to the next time step. This triggers the Model Update Logic to calculate new values for the state variables of all agents and hydrologic units, as well as any regional- and global-level state variables. At the beginning of the next time step, the facilitators may choose to review the overall state of the watershed system with the participants, exploring any notable changes in system-level outcomes interest. Through their specialized interface, the facilitators also have the capability to initiate exogenous, system-level events, such as hurricanes, floods, droughts, and so on, at any time step in the game play.

This process, in which all game participants first make their decisions for a given time step, the game facilitators advance the model to the next time step, and then review the results, continues iteratively throughout the game play. The game play ends once the model advances through all time steps in the period under consideration. At the end of each game play, the facilitators hold a debriefing with the participants, reviewing the system-level outcomes of the watershed system over time. The facilitators and participants reflect on the results, and the facilitators challenge the participants to consider how their individual and collective decision-making in their stakeholder roles contributed to the watershed system's fate.

4. Technical Approach

4.1 Overview of the Technical Approach

Technical systems to implement the Global Water Games conceptual modeling framework and support model use are currently under development. This software infrastructure will allow modelers to share and reuse common, extensible, and flexible technical components between different Global Water Games models—making setting up a model for a new watershed system much quicker and less costly than building a new model from scratch. At a high level, the technical approach employs a distributed "client-server" strategy built on top of the World Wide Web. During model use, the game facilitators and each participant "log in" to a game play from within a web browser on individual client computers—either public computers available at the game play site, or their own personal computers. The client computers all connect to a central server that hosts the Global Water Games technical infrastructure via the web.

The technical implementation of each Global Water Games model consists of four main components: a *database*, customized *object classes*, the *Core Engine*, and a *user interface*. Global Water Games models use a PostgreSQL database extended by PostGIS. PostgreSQL is an open source relational database system [42]; PostGIS extends PostgreSQL by adding support for spatial Geographic Information System (GIS) objects and queries [43]. The Core Engine and customized object classes are written in the PHP: Hypertext Preprocessor language, commonly known as PHP. PHP is an open source scripting language that supports elements of object-oriented programming, and is well suited for web-based software development [44]. The user interface is written in a combination of PHP, HTML, Cascading Style Sheets (CSS), and JavaScript. All Global

Water Games technical components are built with free and open software tools. I discuss each technical component in detail below.

4.2 The Database

The Global Water Games infrastructure relies on a relational database. Each Global Water Games model will have a single database to store all data required for, and generated by, each individual game play. This database serves two main purposes. The first is to store data during individual game plays and make the data available to the Core Engine. The data stored and made available includes reference data about the model, such as lists of HUs and all agents, and the values of all state variables, both spatial and agent, across all time steps. The database's second main purpose is to serve as a long-term repository for all data generated by the simulation model, across all game plays, and to make that data available for later analysis.

At the beginning of each game play, new records containing the initial values for all state variables used in the model will be added to various tables in the database. As the model progresses through a game play, new data will be inserted into the database—including updated values for all state variables, plus the decisions made by all agents—at each time step. To define the relationships between data elements represented in different tables, each Global Water Games database makes heavy use of primary keys and foreign keys. Primary keys are data elements that uniquely identify records in the local database table. Foreign keys are data elements in the local table that refer to the primary key of a different database table, thus relating records in the local table with unique records stored in the other table. The database for each Global Water Games model contains at least three sets of tables: General Tables, Spatial Tables, and Agent Tables.

4.2.1 General Tables

The set of General Tables contains overall reference data about a Global Water Games model and its use. For a given model, the General Tables include at least the following individual database tables:

- **Game Play Table** — The Game Play table contains a record for each individual game play of the model. The Game Play Table includes a field for Game Play Key, which is a primary key identifying each individual time the game has been played. The Game Play table may include additional fields for reference information about individual game plays, such as date and location. The Game Play Table is dynamic—a new record will be added each time the game is played.
- **Time Step Table** — The Time Step Table contains a unique record for every time step for each game play of the model. The Time Step Table includes fields for Time Step Key (primary key), Game Play Key, and two timestamps, Start Time and End Time. The Game Play Key is a foreign key that designates the specific game play to which each time step belongs. The two fields for timestamps indicate the literal times at which each time step began and ended within a game play. The Time Step Table is dynamic—a new record will be added for each new time step during each game play.
- **GIS Table** — The GIS Table contains, at minimum, a GIS record for each hydrologic unit in the Global Water Games model. It may also contain GIS records for other geographic regions of interest, such as larger, aggregated watershed areas, or administrative districts like US States. It will contain fields for GIS Object Key

(primary key), GIS Object Name, as well as specialized GIS data types. The records in the GIS table will not be used directly in model operations, but will be useful for the user interface to draw maps and visualize data on the fly during game play. The GIS Table is static—it will not change during a game play or from one game play to the next.

4.2.2 Spatial Tables

The set of Spatial Tables stores all data required to completely specify the elements of the Spatial Module as described in the Conceptual Framework chapter, across all time steps during an individual game play and between different game plays. For a given model, the Spatial Tables set includes at least the following individual database tables:

- **Hydrologic Units Lookup Table** — A lookup table containing a unique record describing each hydrologic unit in the model. The HU Lookup Table, at minimum, includes fields for HU Key (primary key), HU Name, and GIS Object Key. The GIS Object Key is a foreign key that indicates which GIS data the user interface should use for drawing maps and visualizing data for each HU in the Lookup Table. The HU Lookup Table is static—it will not change during a game play, or from one game play to the next.
- **Hydrologic Link Lookup Table** — A lookup table that specifies the upstream-downstream relationships between the hydrologic units in the model, as described in the Conceptual Framework chapter. The Hydrologic Link Lookup Table includes fields for Hydrologic Link Key (primary key), Upstream HU Key, and Downstream HU Key. The Upstream and Downstream HU Keys are foreign keys that link to two

HUs in the HU Lookup Table, and indicate the upstream-downstream relationship between them. This information is required for certain spatial variables for which “upstream effects” play a role. The Hydrologic Link Lookup Table is static—it will not change during a game play, or from one game play to the next.

- **Spatial Variable Types Lookup Table** — A lookup table containing a unique record for each type of Spatial Variable used in the model. The Spatial Variable Types Lookup Table includes fields for Spatial Variable Type Key (primary key) and Spatial Variable Name. The Spatial Variable Types Lookup Table is static—it will not change during a game play, or from one game play to the next.
- **Spatial Variables Table** — The Spatial Variables Table contains records for all spatial variables for all HUs, across all time steps, for every game play of the model. The Spatial Variables Table includes fields for Spatial Variable Key (primary key), Spatial Variable Type Key, HU Key, variable value, Time Step Key, and Game Play Key. The Spatial Variable Type Key and HU Key are foreign keys that connect the spatial variable record with its spatial variable type and the HU to which it belongs, respectively. The value field stores the value of the spatial variable. The Time Step Key and Game Play Key are foreign keys that indicate at which time step the spatial variable held the given value, and during which game play, respectively. The Spatial Variables Table is dynamic—new records will be added for all new spatial variable values generated during each game play.

A given Global Water Games model may include additional geospatial units of interest, beyond the basic set of HUs, that contain their own unique variable types. For example, a model for the Chesapeake Bay Watershed System would need to include the Chesapeake Bay itself as a spatial unit, with its own unique variables, such as the size of the anoxic region in the Bay. To accommodate such special regions, the set of Spatial Tables may include additional analogous Geospatial Unit Lookup Tables, Variable Type Tables, and Variable Tables as needed.

A visual depiction of the General Tables and Spatial Tables, and the relational links between them, is shown in Figure 9.

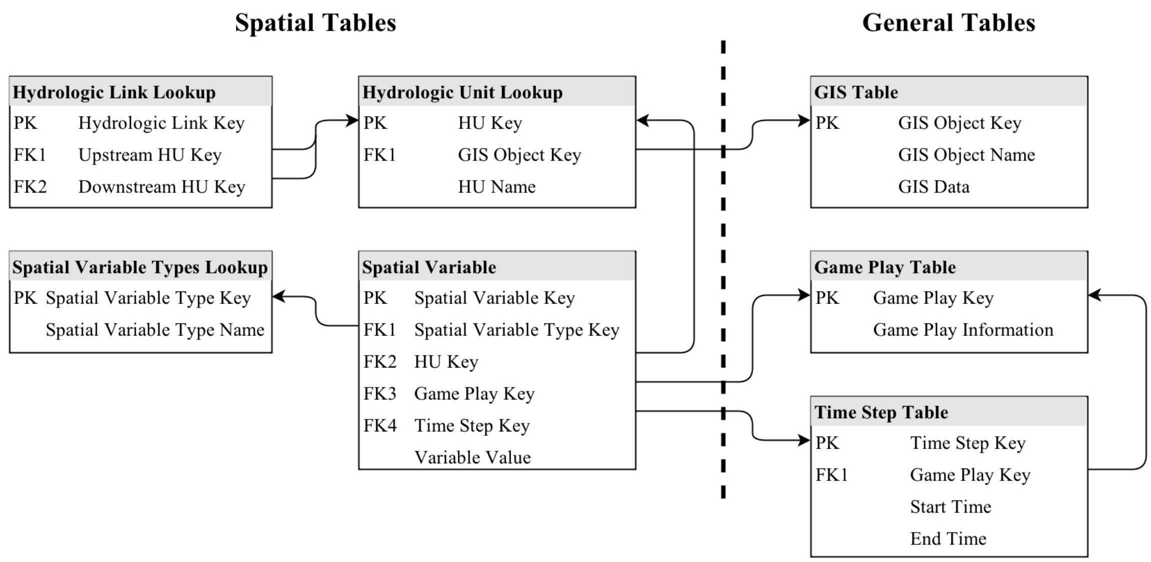


Figure 9. A visual depiction of the General Tables and Spatial Tables in the Global Water Games database. Each box represents one table. The arrows between the tables show the relational links between foreign keys in one table to primary keys in another table.

4.2.3 Agent Tables

The set of Agent Tables stores all data required to completely specify the elements of the Stakeholder Component as described in the Conceptual Framework chapter, across all time steps during an individual game play and between different game plays. For a given model, the Agent Tables set includes at least the following individual database tables:

- **Agents Lookup Table** — A lookup table containing a unique record describing each agent in the model. The Agents Lookup Table, at minimum, includes fields for Agent Key (primary key), Agent Name, Stakeholder Role Key, and HU Key. The Stakeholder Role Key is a foreign key that links each agent to its stakeholder role; the HU Key is a foreign key that designates the agent's "home" hydrologic unit. For each Global Water Games model, the Agents Lookup Table is static—it will not change during a game play, or from one game play to the next.
- **Users Table** — The Users Table contains a unique record identifying each human participant for a given game play of a Global Water Games model. The Users Table, at minimum, includes fields for User Key (primary key), User Name, Agent Key, and Game Play Key. The Agent Key is a foreign key that links the human users listed in the Users Table to the agents they control during a given game play. The Game Play Key is a foreign key that identifies which particular game play of the model each user record is associated with. The modelers may choose to add fields to the Users Table to store any additional information about the game participants that needs to be recorded. The Users Table is dynamic—new records will be added for the new set of participants every time the Game is played.
- **Stakeholder Roles Lookup Table** — A lookup table containing a unique record for each type of stakeholder role used in the Global Water Games model. The Stakeholder Role Lookup Table contains fields for Stakeholder Role Key (primary

key) and Stakeholder Role Name. The Stakeholder Role Lookup Table is static—it will not change during a game play, or from one game play to the next.

- **Agent Variable Types Lookup Table —** A lookup table containing a unique record for each type of agent variable used in the model, across all stakeholder roles. The Agent Variable Types Lookup Table contains fields for Agent Variable Type Key (primary key), Agent Variable Type Name, and Stakeholder Role Key. The Stakeholder Role Key is a foreign key that links each Agent Variable Type to the correct Stakeholder Role the agent variable type is associated with. The Agent Variable Types Lookup Table is static—it will not change during a game play, or from one game play to the next.
- **Decision Types Lookup Table** — A lookup table containing a unique record for each type of decision that agents can make in the model, across all stakeholder roles. The Decision Type Lookup Table includes fields for Decision Type Key (primary key), Decision Type Name, and Stakeholder Role Key. The Stakeholder Role Key is a foreign key that identifies which particular stakeholder role makes each kind of decision. The Decision Type Lookup Table is static—it will not change during a game play, or from one game play to the next.
- **Agent Variables Table** — The Agent Variables Table contains records for all agent variables for all agents, across all time steps, for every game play of the model. The Agent Variables Table includes fields for Agent Variable Key (primary key), Agent Variable Type Key, Agent Key, variable value, Time Step Key, and Game Play Key. The Agent Variable Type Key and Agent Key are foreign keys that connect the agent variable record with its agent variable type and the agent to which it belongs,

respectively. The value field stores the value of the agent variable. The Time Step Key and Game Play Key are foreign keys that indicate at which time step the agent variable held the given value, and during which game play, respectively. The Agent Variables Table is dynamic—new records will be added for all new agent variable values generated during each game play.

- **Agent Financials Table** — The Agent Financials Table is identical to the Agent Variables Table, but it contains records solely for agents' financial positions. Financials are split out into a separate table because virtually all stakeholder roles will have a Financial Position agent variable, and to ease calculations that focus only on financial values.
- **Decisions Table** — The Decisions Table contains a record for every decision that every agent makes, across all time steps, for every game play of the model. The table contains fields for Decision Key (primary key), Agent Key, Decision Type Key, decision value, time step, timestamp, and Game Play Key. The Agent Key and Decision Type Key are foreign keys that link each agent decision record to the correct agent and indicate the decision type, respectively. The decision value field stores the result of the decision the agent made—for example, a number of acres bought or sold, or choosing one particular type of agricultural land management practice over others. The time step field indicates the time step in the model at which the agent made the decision. The timestamp field records the literal time at which a human user controlling an agent made the decision, so that the modelers can later analyze how much time users spent deliberating on their decisions. The Decisions Table is

dynamic—new records will be added for all new decisions agents make during each game play.

A visual depiction of the Agent Tables, the relational links between them, as well as the links from them to the General and Spatial Tables, is shown in Figure 10.

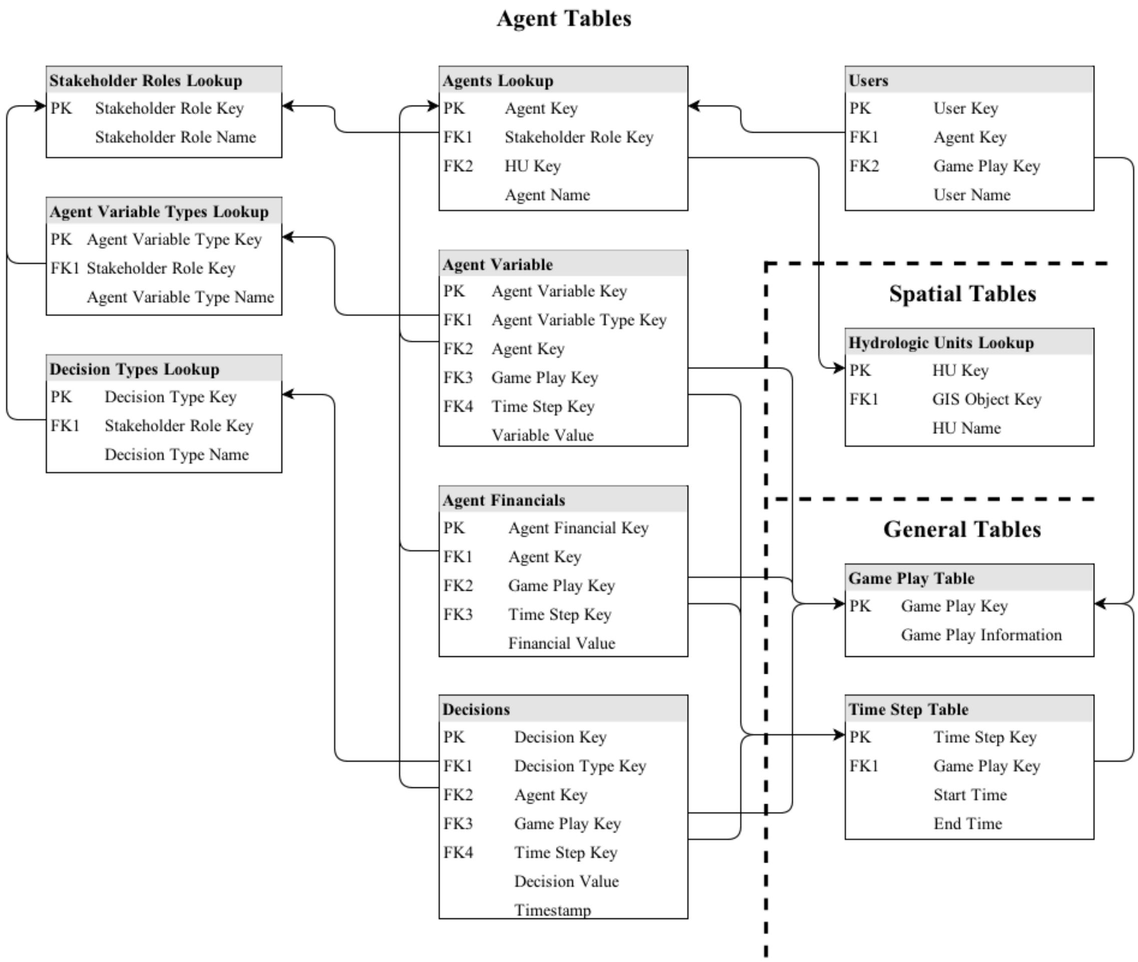


Figure 10. A visual depiction of the Agent Tables in the Global Water Games database. Each box represents one table. The arrows between the tables show the relational links between foreign keys in one table to primary keys in another table. Relational links from the Agent Tables to the General Tables and Spatial Tables are also shown.

Taken together, the data stored in the General Tables, the Spatial Tables, and the Stakeholder Tables in a Global Water Games model's database contain all the information required to fully specify the state of the watershed system model at every time step. In addition, the database contains records of all human participants for each game play, and stores all of the decisions they made. After each game play, the database retains all of this information for further analysis at a later date. As a Global Water Games model is played again and again, the database represents an ever-increasing data set describing how the model of the complex socio-ecological watershed system responds under different conditions, such as differing public policy regimes or extreme exogenous events.

4.3 Object Classes

The second main component of the Global Water Games technical infrastructure is a set of *object classes*. In object-oriented programming (OOP), discrete entities or concepts are represented in programming code as *objects*. Objects have a number of associated *attributes*, which are data elements that describe the object. In addition, objects have a number of *methods*, or functions, that can retrieve or modify an object's attributes, or interact with other objects, during program execution. Objects can belong to *classes*, which are categories of objects that define a set of common attributes and methods. Classes themselves can belong to other classes, setting up a class hierarchy of *superclasses* and *subclasses*. A subclass that belongs to a superclass will *inherit* all of the superclass's attributes and methods; it can also *extend* the superclass by adding new attributes and methods, or by modifying existing ones. All objects that belong to a given class will have the common attributes and methods associated with the class, as well as attributes and methods inherited from any superclasses.

An object-oriented, class-based programming architecture is a natural fit for the computational needs of the Global Water Games modeling framework. Each of the key elements in the conceptual modeling framework—each hydrologic unit, each agent, the entire watershed itself—is represented as an object in the program code. The state variables and other relevant information about each modeling element are stored as attributes of its associated object, with customized methods to allow those attributes to be retrieved and modified. Object classes are defined for the various sets of modeling elements that share similar characteristics, such as classes for all hydrologic units or all the agents of a given stakeholder role, allowing the individual objects that represent the modeling elements to inherit a common set of attributes and methods from their class. Each Global Water Games model will contain at least the following types of object classes:

4.3.1 Spatial Unit Classes

The model contains a Spatial Unit Class that serves as the superclass for all types of geospatial units of interest in the model. At a minimum, the Spatial Unit Class features one subclass for the set of base-level hydrologic units. The HU Class has a name attribute that associates HU objects with one of the HU records in the HU Lookup Table in the database, as well as attributes for each of the spatial variables associated with HUs in the model. It may also feature further attributes to store additional information of interest about the HUs as needed. The class contains a number of methods; at a minimum it has two methods per attribute—a Get method to retrieve and return the current value of the attribute, and an Update method to update the current value of the attribute for the next time step. The Update method first interacts with other objects, such as agent objects that represent agents located within the HU in question, or other hydrologic unit objects, to retrieve any required information. It then performs the calculations to update the attribute in question for the next time step, and sets the attribute to the new value. For spatial variable attributes, these Update methods implement the general "spatial variable update function" described in the Conceptual Framework chapter. In addition to the HU Class, a Global Water Games model may include additional subclasses for other types of geospatial units, such as administrative regions or the entire watershed itself. These specialized spatial unit classes would have their own attributes and methods, analogous to those found in the HU Class, to handle the data of interest that describe the geospatial units that objects of these classes represent.

4.3.2 Agent Classes

In addition to the Spatial Unit Class and its subclasses, the model features an Agent Class that serves as a superclass for all agents in the model. This Agent Class has at least two subclasses: a Regulator Class for agents in a regulatory stakeholder role, and an Actor Class for other types of stakeholder role used in a given Global Water Game. In turn, these classes have subclasses of their own corresponding to each individual stakeholder role—such as Land Regulator and Water Regulator subclasses for the Regulator Class, and Crop Farmer, Land Developer, etc., subclasses for the Actor Class. This class hierarchy strategy allows attributes that apply to most or all agents, such as financial position, to be consolidated into higher superclasses; more specific attributes, such as acreage of soybeans under cultivation, are associated with the most specialized subclasses.

For a given stakeholder role, the corresponding Stakeholder Role Subclass has at least four kinds of attributes, some of which are inherited from superclasses:

- A name attribute, which associates Agent Objects with one of the Agent records in the Agents Lookup Table in the database.
- Agent variable attributes, with one attribute for each of the agent variables associated with that stakeholder role.
- Decisions attributes, with one attribute for each of the decisions that agents of the given stakeholder role make at each time step. The decision attributes store the outcome of an agent's decisions at the current time step.
- Impact attributes, with one attribute for each of the spatial variables in the local HU that can be affected by the types of decisions an agent in the given stakeholder role makes. The impact attributes store an agent's individual contribution to changes in the local HU's spatial variables at the next time step.

Similarly to the Spatial Unit Classes, the Agent Classes also contain at least two methods per attribute—a Get method and an Update method, which retrieve the attribute's current value and compute the next value for the attribute, respectively. For agent variable attributes, the Update methods implement the general "agent variable update function" described in the Conceptual Framework chapter. For decision attributes, the Update methods simply set the attribute's value to the outcome of the agent's relevant decision at the current time step. The Update methods implement the functions the modelers selected during model creation to map the impact of individual agent decisions onto the values of spatial variables in the local HU.

The Spatial Unit Class and Agent Class, and their subclasses, serve as the computational framework for the Spatial Module and Stakeholder Module, respectively. The object classes work closely with the Core Engine to implement the Model Update Logic during each game play.

4.4 The Core Engine

The Core Engine is the computational heart of a Global Water Games model. The Core Engine is responsible for both initializing the model at the beginning of each game play, and performing the calculations and commands required to advance the Global Water Games model from one time step to the next. Together with the update methods in the Object Classes, it serves as the technical implementation of the Model Update Logic module described in the Conceptual Framework chapter.

At the beginning of each new game play for a Global Water Games model, the Core Engine initializes and prepares the model's technical infrastructure for the game play. In the database, the Core Engine creates a new record in the Game Play table to serve as the key for the upcoming game play. It creates new records in the User Table, one for each participant taking part in the game play, and assigns each participant to a particular agent and stakeholder role by linking their record in the User Table with one of the agent records in the Agents Lookup Table. It also creates new records in the Spatial Variables Table, the Agent Variables Table, and the Agent Financials Table that correspond to all the spatial variables and agent variables used by all hydrologic units, other geospatial units, and agents in the model, and sets them to their initial values. These records set the initial state of the system for the new game play. In addition, the Core Engine uses the various Object Classes to create objects corresponding to every modeling element used in the model, including every hydrologic unit, agent, and any other geospatial units. When the Core Engine initializes these objects, it sets their "name" attributes to explicitly link them with corresponding records in the appropriate lookup tables in the database—each HU object will be named after one of the HU records in the HU Lookup Table, each agent object will be named after one of the agent records in the Agent Lookup Table, and so on. The Core Engine then sets the new objects' state variable attributes to the corresponding initial variable values stored in the database for the modeling element to which they are linked.

During an active game play, the Core Engine is the component that actually steps the model forward through time. It contains a special "Advance Model" function that iterates through the set of all objects in the Global Water Games model, calling the Update methods for all state variable attributes for each object. This updates all state variables in the model to their next values, hence updating the full state of the watershed system. The Core Engine uses an "inside-out" approach to updating the various modeling elements, updating the smallest elements first before proceeding to update the next level of larger modeling elements. It starts by looping through the set of all agent objects, then loops through the set of all HU objects (starting with the furthest upstream, then moving stepwise to update HUs further down the hydrologic link network), then finally looping through any larger spatial aggregation areas or global objects used in the model. Figure 11 shows a diagram of the Core Engine's iterative, "inside-out" updating approach.

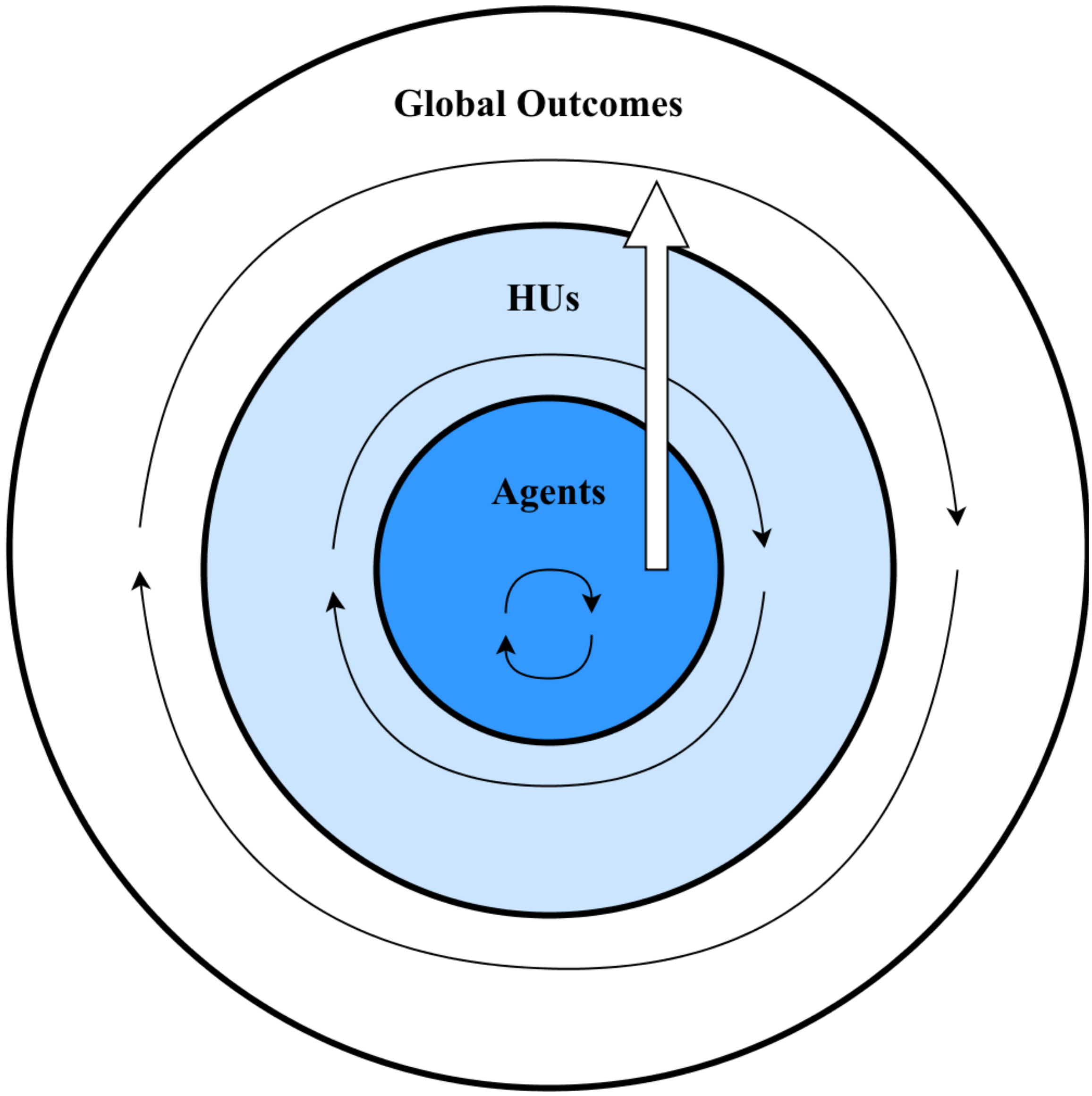


Figure 11. A diagram depicting the Core Engine's iterative "inside-out" updating strategy, looping through smaller modeling elements before moving on to larger ones.

As the Core Engine updates the objects, it writes the new variable values returned by the objects' Update methods to the appropriate database tables for storage. Finally, once it has looped through the entire set of objects in the model and updated all state variables, and written the new values to the database, it pushes the new values to the user interface to begin the next time step.

4.5 The User Interface

The role of the user interface in the Global Water Games technical infrastructure is twofold: to provide the human participants with the information and tools they need to make decisions and play the game, and to give the game facilitators a degree of control over the game play experience. There are different and specialized interfaces for the facilitators and the participants, and subtler differences between the interfaces for participants in different stakeholder roles. In all cases, the user interface accepts input from human users, either the facilitators or the participants, and passes that information along to the other technical components.

The participant user interface is web-based, built with a variety of open source, dynamic web technologies. During each game play, the participants log in to the interface from individual computers using a web browser. For each participant, the interface is customized to present state-of-the-system information relevant to the stakeholder role and location (i.e., home HU) of the agent to which the participant is assigned. The interface also provides the participants with tools—typically text boxes, drop down menus, etc.—to enter their preferred choices in response to the series of decisions that they make at each time step based on the stakeholder role of their agent. For example, to a participant controlling an agent in the Crop Farmer role, the user interface may present information about the agent's financial position, the number of acres the agent is cultivating of a number of crops, the flow rate in the local HU, the nitrogen load in the local HU, and so on. The interface would also present tools for the participant to input the decisions assigned to their stakeholder role, such as allocating the amount of acreage devoted to each crop, a choice between conventional or organic land management practices, etc. Once a participant is satisfied with their decisions for the current time step, the interface provides a button to “submit” the decisions. This submission then calls the Update methods for the decision attributes in the agent object that represents the participant’s agent, thus passing information on player decisions to the rest of the technical infrastructure. Figure 12 shows the user interface for a Crop Farmer agent from the original UVa Bay Game®, upon which the Global Water Games participant user interface, still under development, is based.

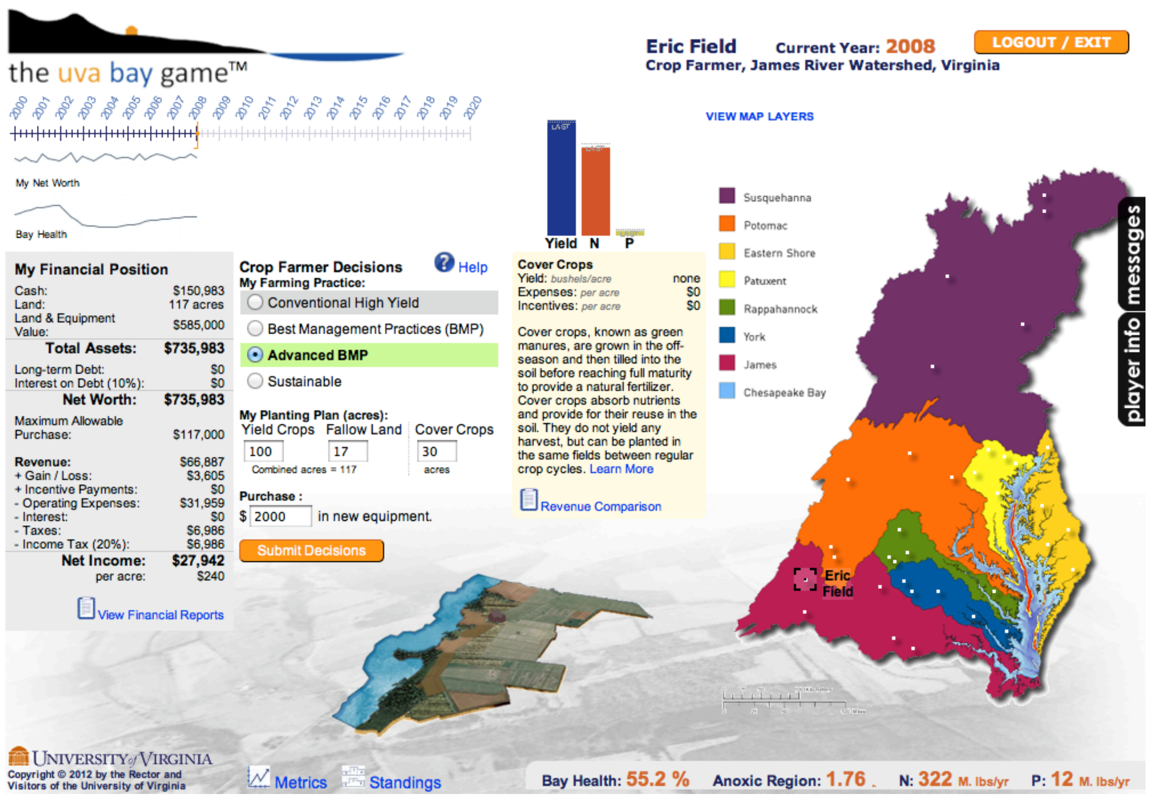


Figure 12. The participant user interface for a Crop Farmer agent during a game play in the existing UVa Bay Game. The Global Water Games participant user interface will be closely based on the interface of the existing UVa Bay Game®. The participant user interface presents the user with a variety of relevant data about agent variables (e.g. My Financial Position), global variables (e.g. Bay Health), and provides a method for inputting decisions (Crop Farmer Decisions section). Also visible is the “messages” tab participants can use to communicate with one another via text-based messages.

The game facilitators also have their own specialized, web-based user interface for use during game plays. The facilitators’ interface serves three purposes. First, it enables the facilitators to share summary information about the state of the watershed system with the participants during a game play, such as system-level indicators of watershed health. For example, Figure 13 shows a view in the facilitator interface displaying graphed data from numerous system-level state variables over time during an active game play in the existing UVa Bay Game®. Figure 14 shows the "standings" page from the existing UVa Bay Game®, which displays similar types of data, but broken down by constituent watershed to see their individual contributions to the overall condition of the Bay. The facilitator interface gives the facilitators the option to share and review this data with the participants at each time step.

Figure 13. A view in the facilitator interface displaying graphed data for several system-level state variables over time during a game play in the existing UVa Bay Game®. The facilitators have the option to review this data with the participants at each time step.

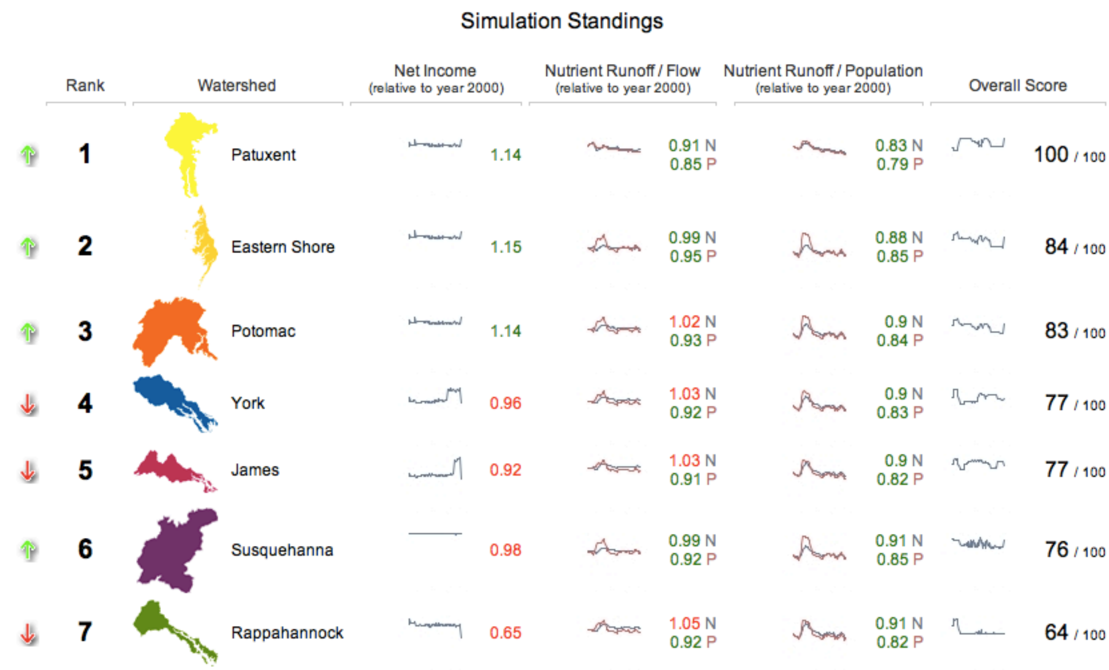


Figure 14. The “standings” page, an example view from the facilitator user interface during a game play in the existing UVa Bay Game®. The standings page displays critical data about watershed system health, such as Net Income, various nutrient metrics, and an Overall Score, and gives the facilitators the option to share this information with the participants.

Second, the facilitators’ interface allows them to control the pace of the game play. Once all participants have had time to make their decisions during a time step, the facilitators’ interface allows them to invoke the Core Engine’s Advance Model function to update all state variables and move the game play to the next time step. Finally, the facilitators’ interface gives the facilitators the option to trigger exogenous extreme events in the model, such as hurricanes, floods, droughts, and so on, that affect the state of the watershed system.

Thanks to the modeling framework's web-based user interface, the game facilitators have substantial flexibility when making arrangements for the location and computing resources for a Global Water Games game play. Each participant can "log in" and engage in a game play from any location where they have access to an internet connection and web browser, on either a public computer provided for the game play or their own personal computer. This gives the facilitators several options when scheduling a game play—they can arrange an "in-person" game play at a central location where the facilitators and participants will be physically present, such as at a library, university, or corporate facility, or a "remote" game play, where all participants will log in remotely from their own personal computers, or some combination of the two. For game plays that include remotely-based players, using third-party online videoconferencing and/or screen-sharing services is recommended to make the game play experience as interactive and inclusive as possible for remote players. The Global Water Games user interface also has a built-in text communication feature, which enables participants to send text-based messages to any other participants, including the game facilitators. When possible, in-person game plays are preferred, as having all participants physically present eases communication between the facilitators and participants, and among the participants themselves during game play. But for situations in which holding a game play at a single location is not convenient or possible, the modeling framework provides support for remote plays.

4.6 Extending the Platform

Despite sharing many fundamental characteristics in common, every watershed system is different, and will pose its own unique concerns and challenges. It is impossible to anticipate and design for every possible idiosyncrasy in every watershed system a priori. To this end, both the conceptual and technical framework of the Global Water Games platform is designed to be flexible and extensible. If future decision makers and stakeholders in a watershed system wanted to explore the feasibility of a market-based system to allocate water use rights, or study the impact of bringing new water desalination plants online, for example, it would be a straightforward process to add a Market Module or an new stakeholder role and object class for desalination plants to the modeling platform. By adding new (or modifying existing) object classes, stakeholder roles, agent decisions, variable update input functions, etc., the modelers can extend the platform to include a wide variety of new or different aspects of watershed systems.

5. Next Steps

5.1 Rebuilding the UVa Bay Game® as a Global Water Game

The first Global Water Games model under development is a recreation of the original UVa Bay Game® using the new modeling platform. A set of 55 HUC-8 hydrologic units in the national Watershed Boundary Dataset that make up the Chesapeake Bay Watershed has been identified (2 HUC-8 units for the Bay itself, and 53 for the land that drains into it) [39]. Various datasets of interest have been mapped into the 53 land-based HUs, including population data from the 2010 US Census and land use data from the 2006 National Land Cover Database, the most recent comprehensive land use data available [45]. Stream gauge data from the U.S. Geological Survey have been used to develop flow forecast (i.e., historical trend) functions for each HU [46]. These hydrologic units will serve as the basis for the Spatial Module in the newly constituted Bay Game. Build out and completion of the Global Water Games technical infrastructure will coincide with the development of the new Bay Game.

5.2 Global Water Games for Additional Watershed Systems

After the UVa Bay Game® rebuild, the next step will be to take the Global Water Games platform to other watershed systems beyond the Chesapeake. A Game for the Guadalupe-San Antonio Watershed system in Texas, known as the Texas Water Game, is currently in the planning stages [47]. A Global Water Game for the Murray-Darling Basin in Australia has also been proposed [48].

The Texas Water Game and the Murray-Darling Basin Game will be excellent tests of the Global Water Games platform's flexibility and adaptability to geographically diverse watersheds systems with different stakeholder values and objectives. They offer a huge variety in physical scale: the Guadalupe-San Antonio watershed's land area is only about one sixth the size of the Chesapeake's [49], while the catchment area of the Murray-Darling Basin is more than six times larger than the Chesapeake Bay Watershed [21]. Additionally, the needs of decision makers and stakeholders in the Guadalupe-San Antonio watershed and Murray-Darling Basin are very different from those of their counterparts for the Chesapeake Bay. Stakeholders in the Texan and Australian systems are much more focused on ensuring a sustainable overall *quantity* of water supply—both watershed systems face increasing populations at a time when natural flow rates are likely to decline due to global climate change [21, 47]. For water quality, agricultural nutrient runoff may still be important, but their primary objective is salinity. If the Texas Water Game and Murray-Darling Basin Game are successful, it would validate the Global Water Games platform's ability to provide policy decision support and social learning for a variety of stakeholder values and objectives across geographically diverse watershed systems.

6. Conclusions

This thesis has presented the Global Water Games platform, a general framework and approach for building Global Water Games—watershed system simulation models presented in a "serious game" format and designed to support effective watershed system management. The technical infrastructure of the Global Water Games platform is currently under development, and the first Global Water Games themselves are still being created, so to date it has not yet been possible to *validate* the results of individual Games to real-world data from their watershed systems. The success of the existing UVa Bay Game®, on which the Global Water Games modeling framework is based, validates the overall modeling strategy. However, each Global Water Game will still need to be individually validated to demonstrate that it meets the needs and objectives of the watershed system stakeholders that it serves.

On a conceptual level, the Games produced using the Global Water Games platform, and the platform itself, will meet the criteria for success laid out in Chapter 1. Global Water Games are *spatially explicit*, through the set of hydrologic units that make up the Spatial Module. They are *dynamic*, as the Model Update Logic and Core Engine enable the state of the watershed system to change as a game play steps forward through time. They are *agent-based,* through the set of stakeholder-agents contained in the Stakeholder Module. They are *participatory* by allowing human players to take control of individual agents in the Stakeholder Module during each game play; the platform also calls for stakeholder participation during model creation. The Games provide *policy decision support,* by serving as a "laboratory" to explore and test new policy ideas, and support *social learning* by allowing stakeholders to grapple with the complex, interconnected nature of watershed system management problems during game plays. The platform itself is *flexible,* as its common conceptual and technical components can be used to build Global Water Games across diverse geographies and supporting a variety of stakeholder needs and objectives. It is also *scalable,* as these components can be rapidly reconfigured and redeployed to build a simulation model for a new watershed system. Finally, the platform is *extensible*, as it is straightforward to add new functionality through new object classes, stakeholder roles, variable update functions, and so on, to extend the platform.

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Appendix A: Methodology for Creating Global Water Games

This thesis presents an eight-step general methodology to create a Global Water Game for any given watershed system. The recommended steps are (1) define global model parameters, (2) determine relevant stakeholder roles for agents, (3) identify data sources for inputs, (4) build Spatial Module based on hydrologic units, (5) build Stakeholder Module, (6) define Model Update Logic, (7) instantiate the technical infrastructure, and (8) model verification and validation. The first six steps correspond to creating the modules of the Conceptual Framework described in Section 3—the Spatial Module, the Stakeholder Module, and the Model Update Logic. The seventh step then ports these conceptual modules into the components of the Global Water Games technical infrastructure. The first four steps of model creation, from defining relevant model parameters through determining the set of hydrologic units for the Spatial Module, should involve direct stakeholder participation. Stakeholders should also be consulted during the last step, model verification and validation. This section examines each step in further detail.

A.1 Define Global Model Parameters

The first step to building any Global Water Games model is to define what exactly needs to be modeled. The key question to be answered during this step is “What kinds of system outcomes are important to the stakeholders in this watershed?” During the development of each watershed model, stakeholders participate directly to assist the modelers in determining which measures of watershed “performance” (output variables) are most critical to them.

The particular output variables or set of variables used will differ from one Global Water Game to the next, as no two watershed systems or groups of watershed stakeholders are identical. However, certain similar types of system outcomes are likely to be of interest to stakeholders in a wide variety of different watershed systems. The methodology suggests the following categories of output variables:

- Volume of water flow
- One or more water quality variable(s)
- Economic activity
- Customized watershed outcome variable(s)

Water quality variables may include an assortment of characteristics, such as sediment load, salinity, nitrogen and phosphorus loads, dissolved oxygen, etc. Volume of water flow and a set of one or more water quality variables should be sufficient to address both the sustainability of water supply and a variety of environmental concerns. If stakeholders have a specific concern unique to a particular watershed, volume of water flow and/or a set of water quality variables may be combined to form an output variable customized to reflect the stakeholders' needs. An example of a customized watershed outcome variable would be the size of the anoxic region in the existing UVA Bay Game® model.

Once the desired output variable(s) are known, the stakeholders assist the modelers in determining the relevant input variables that influence the behavior of the selected system outputs. Again, no two watersheds are identical, but a common set of inputs will likely be of interest for many different watershed systems. The methodology suggests the following categories of watershed input variables:

- Volume of water flow
- Water quality variables
- Precipitation/climate
- Population
- Economic activity
- Agricultural activity
- Land use
- Custom/other

Finally, the modelers and stakeholders need to define the time parameters of the model—specifically, the time period of interest over which the Global Water Game will run, and the desired length of one decision-iteration time step in the model.

A.2 Determine Relevant Stakeholder Roles for Agents

After the global parameters for a given watershed model have been established, the stakeholders assist the modelers in defining the set of relevant stakeholder roles to be assigned to agents in the player component of the model. The particular set of stakeholder roles utilized will vary from model to model—see Section 3.3 for more information on stakeholder roles and the Stakeholder Component in general.

A.3 Identify Data Sources for Inputs

Prior to actually building the various Modules of a Global Water Game, the modelers need to identify data sources for each of the input variables in a given watershed system. During this step, the stakeholders assist the modelers in identifying any local or specialized data sources that may be available. For watershed systems in the United States, a wide variety of data sources are available from government agencies to aid in model creation. A non-comprehensive list of several examples includes:

- Geographic extent (by hydrologic unit) — USGS Water Resources (http://water.usgs.gov/GIS/huc.html)
- Volume of water flow — USGS WaterWatch (http://waterwatch.usgs.gov/new/index.php?id=ww)
- Phosphorus and nitrogen data — EPA Nitrogen and Phosphorus Pollution Data Access Tool (http://gispub2.epa.gov/npdat/)
- Population and economic activity — U.S. Census Bureau American FactFinder (http://factfinder2.census.gov/faces/nav/jsf/pages/index.xhtml)
- Land use — USGS Land Cover Institute (http://landcover.usgs.gov/index.php)

Certain types of data, such as population, economic data, etc., are commonly aggregated and published based on administrative units, such as counties/FIPS codes, census tracts, and ZIP codes. Where practical, the modelers should opt for data aggregated according to the smallest administrative units possible. Using smaller administrative aggregation units results in a higher-fidelity model when the data is migrated into hydrologic units in Step 4.

For watersheds outside the United States, analogous data sources will be identified where possible. If a predefined map of the geographic extent of a watershed by hydrologic unit is unavailable, the modelers can develop their own maps of hydrologic units from a Digital Elevation Model (DEM), using the “Flow Direction,” “Pour Point,” and "Watershed" operations in the ArcGIS software suite (or analogous GIS software suite). DEMs are available for most locations worldwide.

A.4 Build Spatial Module Based on Hydrologic Unit

Once the modelers acquire data for the input variables, they must build the Spatial Module based on hydrologic units. HUs are inherently multi-scale in nature, so the stakeholders will assist the modelers to determine the appropriate scale of HU to provide the degree of spatial fidelity required to meet their needs and objectives. As a guideline, the finest scale of HUs in a simulation model should be larger than the largest scale of administrative aggregation units for data identified in Step 3. For large watershed systems in the United States, such as the Chesapeake Bay Watershed, the HUC-8 level of hydrologic units provided by the U.S. Geological Survey may be an appropriate scale to use as the basic modeling unit.

To build the Spatial Module, the modelers must migrate the input data obtained in Step 3 into the appropriate hydrologic units. This can be achieved by using Geographic Information System (GIS) software, such as the ArcGIS suite or analogous GIS software. The starting point for this process is a geographically explicit GIS map of the HUs that constitute the watershed system, which can be obtained from the U.S. Geological Survey or generated via digital elevation models (see Step 3). The input data obtained in Step 3 likely comes in two forms: "georeferenced," or spatially explicit data, and "non-georeferenced," or non-spatially explicit data, which is aggregated by some type of administrative units. Both types of data can be migrated into the appropriate HUs; the details for these procedures are included below.

- **Georeferenced data** — Certain types of data, such as satellite imagery of land use and locations of point-pollution sources, are likely published in a spatially explicit GIS file. These types of data are straightforward to migrate into the correct HUs. Once the map of the HUs and the relevant input data source are loaded into GIS software as separate layers, a "Spatial Join" or analogous GIS operation will assign the relevant georeferenced input data to the corresponding HU in the HU layer.
- **Non-georeferenced data by administrative unit** — Much of the input data, such as population and economic statistics, is likely aggregated and published by administrative units, such as counties or census tracts. To migrate such data into HUs, an intermediate step must be used: joining the non-georeferenced data to a georeferenced representation of the corresponding administrative units. The modelers need to locate a spatially explicit GIS map of the relevant administrative units. For the United States, such GIS files can be obtained from the U.S. Government's Geospatial One-Stop Portal (http://geo.data.gov/geoportal/catalog/main/home.page). The non-georeferenced data must be moved to the corresponding georeferenced layer of administrative units using a "Table Join" operation based on a common "key" field, such as a unique numeric identifier for each unit. Once the data has been incorporated into the georeferenced layer of administrative units, it can be migrated into the hydrologic units layer using a "Spatial Join" operation, similar to the procedure for georeferenced data.

Once the modelers have migrated all categories of input variables into the correct HUs in the GIS map, the modelers can export the Spatial Module data from GIS software into a table using any standard spreadsheet format. Any additional geospatial units of interest, such as political districts or administrative regions, are also identified at this step. See Section 3.2 for more information about the Spatial Module.

A.5 Build Stakeholder Module

To build the Stakeholder Module for a particular Global Water Game, the modelers must decide how many total agents to use, how many to assign to each of the stakeholder roles, and how the agents should be distributed throughout the HUs. The answers to these questions depend on the characteristics and needs of the particular watershed system, and will vary from Game to Game. The characteristics of the spatial component will provide guidance—for example, it may be appropriate to locate more agents assigned to an "industrial" role in HUs with a greater degree of economic activity in industrial sectors, and to locate more agents assigned to an "animal farmer" role in HUs with a greater proportion of land use devoted to agriculture. See Section 3.3 for more information about the Stakeholder Module.

A.6 Define Model Update Logic

One of the most challenging steps in creating a Global Water Game is defining the Model Update Logic that is used to advance the simulation model from one time step to the next. The particular set of updating rules used will depend on the circumstances of the particular watershed system, and will vary from model to model. The Model Update

Logic contains a general spatial variable update function for each type of spatial variable used in the model, which is composed of intermediate input functions. For each type of spatial variable, the modelers define an intermediate input function for Agent Decisions, Local Natural Forces, Upstream Effects, Historical Trends, and Exogenous Factors. Similarly, the Model Update Logic contains a general agent variable update function for each type of agent variable used in the model. For each type of agent variable, the modelers define an intermediate input function for Agent Decisions, Spatial Variables, and Exogenous Factors. The modelers may decide to create these intermediate input functions themselves, or use existing, scientifically validated models related to the variables in question. For more information about the Model Update Logic and intermediate input functions, see Section 3.4.

A.7 Instantiate Technical Infrastructure

The six preceding steps of the process involve creating the various modules of the Conceptual Framework described in Section 3; the seventh step is porting these conceptual modules to an instantiation of the Global Water Games technical infrastructure. This involves at least three tasks:

- A new instance of the Global Water Games database must be created, and its various tables populated with the appropriate initial conditions. See Section 4.2 for more information on the Global Water Game database.
- Object Classes must be created for each type of geospatial unit and agent used in the new Global Water Game, and their various attributes and methods must be specified. The modelers should largely be able to reuse Object Classes from

previous Global Water Games with minimal modifications; only completely new types of spatial units or stakeholder roles should require a new Object Class to be built from scratch.

- Perform any required modifications to the User Interface to support any new objectives or needs of the stakeholders, any new spatial units or stakeholder roles, etc. The modelers should be able to largely reuse the User Interface from one Global Water Game to the next without major modifications.

The Core Engine is generic, and normally should not require special modification to be reused for a new Global Water Game.

A.8 Model Verification and Validation

Wherever possible, the output of each Global Water Game is validated against historical data and reputable, third party forecasts for system-level outcomes of interest. For example, population forecasts and projections of economic and agricultural activity for many areas are available from U.S. Government agencies. The population, economic, and agricultural outcomes from numerous runs of a Global Water Game should be referenced against projections for similar variables from the U.S. Census Bureau, the U.S. Bureau of Labor Statistics, the U.S. Department of Agriculture, and other agencies to assist in validating the model.

In this final step of model creation, the modelers once again engage the stakeholders to verify that the model addresses their needs and concerns. Additionally, the modelers will consult subject-matter experts familiar with the watershed system under consideration to ensure that preliminary results produced by the model under a variety of circumstances are consistent with reasonable expectations.

Appendix B: Additional Commentary on Temporal Scale

When building a Global Water Games model, one of the many important judgments the modelers and stakeholders make is determining the appropriate temporal scale for the model. Similarly to the spatial scale, the Global Water Games platform offers a large degree of flexibility in the extent and level of granularity for the temporal scale of a model. To review, the Global Water Games platform uses a discrete model for time. A completed Global Water Games model is designed to run through a set time period, for example, a specific span of twenty years. The model divides this complete time period under consideration into a number of basic time steps of an equal, predetermined length. During each game play, the model iteratively steps forward from one time step to the next. The model continues this process until it has moved through all time steps in its time period under consideration, at which point the game play ends.

Three critical aspects of the temporal scale of a Global Water Games model include the length of the basic time step the model uses, the point in time at which the model begins, and length of the overall time period the model covers. The appropriate length of the basic, smallest time step for a Global Water Games model could be based on several factors. It may make sense to synchronize the model's basic time step with the interval of time at which key data is reported. For example, the U.S. Geological Survey reports historical flow rates for all hydrologic units down to the HUC-8 level on a monthly basis [46]. Historical records for other relevant spatial data, such as unemployment rates, climatological data, and so on, may also be reported at a monthly interval. For Global Water Games in which these variables play an important role, using one month as the basic time step would ease developing the historical trend functions and forecast models used for these spatial variables. A second consideration when determining the appropriate length of time step would be the time interval at which real-world stakeholders that the agents in the model represent make the kinds of decisions used in the model. The hydrologically-relevant decisions that stakeholders make—for example, a crop farmer deciding what kind of agricultural land management practices to use—may occur at their own intervals, such as once per annual growing season. To reconcile these two considerations, the modelers may find it practical to use two functional time steps of different lengths in a Global Water Games model. The first is the basic time step at which spatial variables are updated; the second is a longer “decision interval” at which the model stops to allow the agents to make their decisions, and to update their agent variables. Each “decision interval” is an aggregated set of the shorter basic time steps. For example, the original UVa Bay Game® uses a basic time step of one month with a “decision interval” of two years.

The second critical aspect of the temporal scale of a Global Water Games model is the point in time at which the time period under consideration begins. The ideal starting point will vary from one model to the next, depending on the stakeholders’ objectives. However, for Games intended to assist with forecasting future watershed system conditions and/or to test potential future policy decisions, the recommended starting point is in the recent past. Starting a model in the recent past, moving through the present, then forecasting out into the future allows a model to run over a brief period for which empirical data is known, which helps the modelers validate the model and make any necessary adjustments. For example, the existing UVa Bay Game® begins in the year 2000, steps forward through the present, then forecasts out to the year 2020, based on natural forces and the agents' collective decision-making. Beginning in the recent past allows the Bay Game's results from the year 2000 to the present to be compared and validated against observed real-world data from the same period.

Finally, the last consideration in the temporal scale of a Global Water Games model is the length of the overall time period under consideration. For any given Global Water Game, the appropriate time horizon depends on the needs and objectives of the local stakeholders, with whom the modelers consult during model creation. A Global Water Game built for stakeholders primarily concerned about water supply security over the next century due to global climate change will require a different overall temporal scale than a Game built for stakeholders most interested in the impact of population growth and economic development over the next ten years on key water quality metrics.

Appendix C: Additional Commentary on Water Flow Rate

Most Global Water Games models will feature a variety of spatial variables representing both social and ecological metrics. However, for many models, the water flow rate, or "runoff rate," will be the spatial variable that has the greatest impact on the overall outcomes of interest. The water flow rate for a hydrologic unit is defined as the volume of water passing through its single outlet in a given period of time. For Global Water Games focused primarily on security and sustainability of water supply, such as the proposed Texas Water Game or Murray-Darling Basin Game, the water flow rate across the set of HUs *is* the main environmental outcome of interest. Even for models where water quality variables are the key ecological metrics, the water flow rate plays a large role, as the level of flow serves as the "delivery vector" for the water quality metrics under consideration. For example, in the existing UVa Bay Game®, the main ecological spatial variables are the delivered loads of nitrogen and phosphorus into the Bay, which stimulate the algal blooms that ultimately cause hypoxic and anoxic regions to form. However, the delivered loads of nitrogen and phosphorus themselves are heavily dependent on the overall flow rate of water from the watershed into the Bay, so the flow rates are still key.

Due to the outsized role played by the water flow rate spatial variable in many Global Water Games, developing reliable, empirically grounded mathematical models for the flow rate over time for the hydrologic units used in the model is a key task for the modelers during model creation. This is especially true for Global Water Games that are intended to forecast watershed system conditions in the future. These spatial variable forecast models are also referred to generally as the "historical trends" discussed in

Section 3.2. For watershed systems in the United States, the U.S. Geological Survey publishes historical flow rates for all hydrologic units down to the HUC-8 level on a monthly basis [46]. This data can be used to develop time series models for flow rate at the hydrologic unit level, such as ARMA or ARIMA models. These models can be used to forecast flow rates for each hydrologic unit at future time steps, perhaps using expanding uncertainty bands as a game play moves deeper into the future and further from observed, empirical data.

For watershed systems outside of the United States, the modelers need to identify data sources for water flow rate data. There may be government agencies analogous to the U.S. Geological Survey that have flow rate data available; or the stakeholders may be able to help the modelers identify other local sources of data. See Section 3.2 for more information about general historical trend functions and forecasting for spatial variables.